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Origin of brain specialisation for language: A developmental and phylogenetic perspective in monkeys (Papio anubis)

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I, undersigned, Yannick Becker, hereby declare that the work presented in this manuscript is my own work, carried out under the scientific direction of Adrien Meguerditchian and Olivier Coulon, in accordance with the principles of honesty, integrity and responsibility inherent to the research mission. The research work and the writing of this manuscript have been carried out in compliance with both the french national charter for Research Integrity and the Aix-Marseille University charter on the fight against plagiarism.

This work has not been submitted previously either in this country or in another country in the same or in a similar version to any other examination body.

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Abstract

This thesis examines the phylogenetic and developmental origins of hemispheric brain specialisation for homologous language regions in baboons (*Papio anubis*), and how this organisation might relate to gestural communication. In this work, I will focus on the structural lateralisation of key perisylvian structures, that have historically been shown to be crucial for language processing in the human brain: Broca’s area, the Planum Temporale and their white matter fibre connection, the Arcuate Fasciculus. The central questions are: Is this structural hemispheric organisation shared between humans and monkeys? When does it emerge in development, and does it predict later asymmetric behaviours? If so, for what function did it evolve?

The first three studies concerned the development of infant baboons. We have demonstrated in my first study that the Planum Temporale already shows a larger left-than-right surface asymmetry at birth, a key characteristic for the cerebral development of language. Furthermore, the strength of this asymmetry increases with age, similar to human infants. In my second study, we replicated this finding based on grey matter volume measurements of the same region. In my third study we investigated whether this early asymmetry was predictive of later development of handedness for gestural communication. Indeed, those baboons that presented a larger left Planum Temporale at birth, were more likely to become right-handed in communication than those that had an equally large, or larger right Planum Temporale. No effect was found for non-communicative actions. These results are in line with my fourth study that concerned adult baboons and Broca’s homologue. We showed that the marker of Broca’s homologue presented an asymmetry that was associated with contralateral handedness for communicative gesture, but not with handedness for non-communicative, manipulative actions. In other words, in baboons that communicate with the right hand, the marker of Broca homologue is deeper in the left hemisphere and vice versa. Finally, the evolutionary change in the morphology of the Arcuate Fasciculus is the basis of the main theories on the evolution of language. However, via an extensive review, we have shown in my fifth contribution that on the basis of new techniques, the Arcuate Fasciculus is more similar between primates than previously thought. An open question remains, whether its lateralisation differs between human and non-human primates and whether it is linked to gestural communication. The results of my PhD research point to an early emergence of brain lateralisation in monkeys, that is linked to the later development of gestural communication. Therefore, my results support possible gestural origin of language lateralisation, dating back to the common ancestor of humans and baboons, 25-35 million years ago.

Keywords: neuroanatomy, language evolution, asymmetry, development, hemi-
spheric specialization, gestural communication, nonhuman primates, MRI
Résumé

Cette thèse examine les origines phylogénétiques et développementales de la spécialisation cérébrale du langage humain, à travers l’étude des asymétries cérébrales chez les babouins nouveau-né, juvéniles et adultes (*Papio anubis*) et leurs liens potentiels avec la latéralisation de la communication gestuelle. Dans ce travail, je me concentrerai sur la latéralisation des structures périsyliennes clés, qui se sont historiquement révélées cruciales pour le traitement du langage dans le cerveau : L’aire de Broca, le Planum Temporale et leur connexion fibreuse de substance blanche, le Faisceau Arqué. Les questions centrales que je me suis posé pendant cette thèse sont les suivantes : Cette organisation hémisphérique est-elle partagée entre les humains et les singes? Quand émerge-t-elle dans le développement? Permet-elle de prédire les asymétries comportementales ultérieures? Si cette organisation est partagée entre les espèces, pour quelle fonction a-t-elle évolué?

Les trois premières études concernaient le développement de babouins nouveau-né. Dans ma première étude, nous avons démontré que, chez une majorité de babouins, le Planum Temporale présente déjà à la naissance une plus grande asymétrie de surface dans l’hémisphère gauche, une caractéristique clé du développement cérébral du langage. En outre, la force de cette asymétrie augmente avec l’âge, comme chez les nourrissons humains. Dans ma deuxième étude, nous avons reproduit ce résultat en se basant cette fois ci sur la mesure du volume de matière grise de cette région. Dans ma troisième étude, nous avons testé si cette asymétrie précoce prédit le développement ultérieur de la communication gestuelle. En effet, les babouins qui présentaient un Planum Temporale gauche plus étendu à la naissance, devenaient plus probablement droitiers dans la communication que ceux qui avaient un Planum Temporale égal ou plus grand à droite. Aucun effet n’a été constaté pour les actions non communicatives. Ces résultats sont en accord avec ma quatrième étude qui concernait les babouins adultes et l’homologue de Broca. Nous avons pu révéler que le marqueur de l’homologue de Broca présentait une asymétrie associée à la préférence manuelle controlatérale pour les gestes communicatifs, mais pas à celle impliquée dans les actions non communicatives de manipulation d’objet. Autrement dit, les babouins qui communiquent avec leur main droite possèdent l’homologue de Broca plus profond dans l’hémisphère gauche et vice versa. Enfin, le changement de morphologie évolutive du Faisceau Arqué est à la base des principales théories sur l’évolution du langage. Cependant, grâce à une revue de question approfondie, j’ai mis en évidence dans ma cinquième contribution que, sur la base de nouvelles techniques, le Faisceau Arqué est plus similaire entre les primates qu’on ne le pensait. Une question reste ouverte, à savoir si sa latéralisation diffère entre les primates humains et non humains et si elle est liée à la communication gestuelle.
Les résultats de l’ensemble de mes travaux de thèse indiquent une émergence précoce de la latéralisation du cerveau chez les singes, qui est liée au développement ultérieur de la communication gestuelle. Par conséquent, je soutiens l’hypothèse d’une origine gestuelle de la latéralisation du langage, remontant probablement à l’ancêtre commun des humains et des babouins, il y a 25-35 millions d’années.

Mots clés : neuroanatomie, évolution du langage, développement, spécialisation hémisphérique, communication gestuelle, primates non humains, IRM
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8 Discussion

8.1 Is a lateralised perisylvian organisation shared beyond humans and apes, but with Old world monkeys? 
8.2 When does such an asymmetric organisation appear in nonhuman primate development and does it predict later behaviour? 
8.3 If such brain lateralisation is shared with our non-linguistic primate cousins, for what behavioural functions did it evolve, if not for language? 
8.4 Gesture and language 
8.5 Future perspectives

9 Bibliography

ANNEXES (Articles)

A Accelerating the Evolution of Nonhuman Primate Neuroimaging 
B Structural brain asymmetries for language: a comparative approach across primates
"Nevertheless the difference in mind between man and the higher animals, great as it is, certainly is one of degree and not of kind." Darwin, 1871, The Descent of Man, and Selection in Relation to Sex. Vol. 1, page 105.
1. Overview

The writing of the manuscript has been carried out as follows: The first chapter will introduce crucial notions upon which my thesis is based. I will first explain a main cleavage in our field, concerning the (dis)continuity of language evolution. Discontinuous views are mostly based on the sudden appearance of one cognitive or anatomical feature, that strictly divides us from other animals. On the contrary, continuous views plead for a progressive and pluralistic evolution of many cognitive and anatomical feature that together constitute human language. I will next introduce how the comparative phylogenetic approach with nonhuman primate, but also the ontogenetic approach, can advance the question of language evolution. In the following paragraph I will then explain why the study of the brain is crucial in this quest, especially in regards of convergent evolution. To our luck, several initiatives build up large scale databanks of nonhuman primate brains, giving us the infrastructures for investigating such research questions. One of these initiatives is my supervisor’s, Adrien Meguerditchian, project “GestImage”, for which I was hired to help scan the cerebral development of 30 newborn baboons. I focused especially on the origins of the peculiar feature of the human language network: Its asymmetric organisation towards the left hemisphere. In the next section, I review the functions and the structural and functional lateralisation of the main perisylvian language network (Broca’s area, Planum Temporale, Arcuate Fasciculus) in humans including infants. I also compare the data with findings from apes and discuss whether this asymmetric organisation is shared between adult apes, adult humans and human infant. It remains however unclear for what function the language network got specialised in the left hemisphere in the first place. Some authors initially linked such an organisation to handedness for manual actions. However, as it turned out, handedness is a rather poor marker of structural lateralisation for language. Therefore, some authors including my supervisor, have proposed the hypothesis that handedness for gestural communication might constitute a better marker of structural perisylvian lateralisation.

Thus, several questions arise: Is a lateralised perisylvian organisation shared beyond humans and apes, but with Old world monkeys? When does such an asymmetric organisation appear in nonhuman primate development? Will early anatomy drive behaviour or will behaviour shape anatomy? And finally, if such brain lateralisation is shared with our non-linguistic primate cousins, for what behavioural functions did it evolve, if not for language? These questions have formed the main thread of my thesis, with my research articles at the heart of the attempt to provide some answers.

1. In my first PhD study we demonstrate that the Planum Temporale already exhibits a larger left-than-right surface asymmetry in a majority of subject at birth,
a key characteristic of the cerebral development of language. Moreover, its asymmetry strength increases with age, similarly to human infants.

2. In my second PhD study, we have replicated this finding of early Planum Temporale asymmetries based on grey matter volume measurements.

3. In my third PhD study we investigated whether this early asymmetry predicts later development for gestural communication handedness in contrast to handedness for manipulative actions. Indeed, those baboons that showed a larger left Planum Temporale at birth, became more likely right-handed in communication than those that had an equal or larger right Planum Temporale. No effect was found for non-communicative actions.

4. These results are in line with my fourth PhD study that concerned adult baboons and Broca's homologue. We found that the marker of Broca's homologue, the depth of the ventral portion of the inferior arcuate sulcus, showed an interhemispheric asymmetry that was associated with contralateral handedness for communicative gesture, but not with handedness for non-communicative, manipulative actions. In other words, those baboons that are communicating with their right hand have the Broca homologue deeper in the left hemisphere and vice versa.

5. Finally, the Arcuate Fasciculus' evolutionary morphology change is at the base for major theories about language evolution. However, in my fifth contribution, which provides an extensive review of the literature, I highlighted that the Arcuate Fasciculus is more similar between primates than previously thought. An open question remains, whether its lateralisation differs between human and nonhuman primates and whether it is linked to gestural communication.

In the last section, I discuss the theoretical implications that those collective studies may reveal, as well as their perspective directions. First, the structurally lateralised perisylvian organisation seems to be shared with the baboons, an Old world monkey, arguing for a continuous evolution across the primate lineage. Second, early human-like asymmetries are also developing very early in these baboons, at least regarding the Planum Temporale, and seem to shape the later development of lateralisation for communicative behaviour. The findings therefore plead for a continuity in primate brain evolution and its links with the development of communication. Gestural communication might indeed involve cognitive functions related to the evolution of perisylvian lateralisation just as language does. Therefore, this finding points towards a possible gestural origin of language lateralisation, dating back to the common ancestor of humans and baboons, 25-35 million years ago.
2. Introduction

“Human being: n. a man, woman, or child of the species Homo sapiens, distinguished from other animals by superior mental development and language…” (The Oxford Pocket Dictionary of Current English, Oxford University Press 2009)

This exemplary definition makes the obvious clear: we define ourselves as a species by our ability to process language. This means, by implication, that we also distinguish ourselves from other animal species, especially other primates, by the same means. Of course, this group definition and hence demarcation has epistemological, ethical but also ecological consequences (e.g., Morizot, 2020). For example, although most scholared humans are aware of the theory of evolution, we are not sensitive to the close biological continuity between us and other living organisms on the planet (Morizot, 2020).

When Darwin published his theory of evolution, many people felt offended and believed that Darwin's proposed human's descent from apes was an attack on society's moral foundations (e.g., Browne, 2001) See, for example, the famous 1871 satirical illustration in The Hornet magazine depicting Darwin as "A Venerable Orang-outang").

Figure 2.1. – Darwin as "A Venerable Orang-outang"
For at the time when Darwin postulated the kinship between all animals through a common ancestor, western humans needed to distinguish themselves from nature, from their evolutionary kinship. Possibly to the present day, humans of our culture still deliberately ignore the closeness to the "animal" (Challenger, 2021; Parfit, 2012). In fact, experiments on group cohesion have shown that we regard the cognition of our own group (including the largest group: *Homo sapiens*) as superior to that of others. For example, the expression of beliefs about the superiority of a group’s mental power increases oxytocin levels in the group, leading to stronger bonding and commitment to the group's views (De Dreu et al., 2011). Similarly, fears and dangers lead people to renew their group bonds by judging group members as more “human” than outgroup members (Demoulin et al., 2011). In other words, we judge our own group spirit as superior to that of other groups and reinforce this belief when our group feels threatened (e.g., De Dreu et al., 2011; Demoulin et al., 2004). While the group is often a culture or ideology with which we identify, it can also be us as a species (Challenger, 2021).

It is not impossible, that the latter group cohesion and also an unconscious unease (Freud, 1920) about how fine the line between humans and animals is, constitutes the origin of heated debates, when scholars speculate about the origin of language (Challenger, 2021). The word “speculate” is used here deliberately, because heated debates on this topic are also caused by the limited scientific ground on which this fascinating field of research lies (Christiansen and Kirby, 2003). Indeed, ancient cognitive abilities hardly fossilise, nor does brain tissues. Comparisons with found relics from pre-human times are therefore out of the question (Fitch, 2010). This was one of the reasons why, in 1865, the “Société de linguistique de Paris” prohibited research on the origin of language. The debates were so lively, the question so burning. And still in contemporary research, the evolution of language has been suggested as “the hardest problem in science” (Christiansen and Kirby, 2003). I have witnessed first-hand at congresses, how emotionally charged the question of language evolution still is. A major cleavage in this field today, lays in the debate about the evolutionary continuity of language origins (e.g., Montant, 2021). While some authors argue for the human specificity of language, that has suddenly emerged in a discontinuous “great-leap”, others argue for a progressive and continuous evolution that can be backtracked with its precursors in our primate ancestors. Whereas in the discontinuous view a single change took place to enable language evolution, the continuous view argues that the language system is a composite of domain-general features, that must have evolved accordingly to make up language processes. Here, I will briefly describe the two views.

### 2.1. Discontinuous language evolution: The language-ready brain

Since the cognitive revolution in the 1950s, Noam Chomsky has been indisputably influential in the conceptualization of language. The informatic languages at that
time proposed a new formalisation of syntactic rules, which become compatible with the chomskyan conceptions. Chomsky defines a language as a set of (finite or infinite) sentences, each finite in length and constructed out of a finite set of elements (Chomsky, 1957/2009). And further, he defined a language as an inherent capability of native speakers to understand and form grammatical sentences (“Theory of generative grammar” – Chomsky 1965/2014). Thus, despite their differences, the German- and the French language, for example, share the same cognitive “system”, i.e., a certain cognitive operation, specific to the human species, which is biologically predetermined and prewired. Many linguist-trained fellows therefore proposed the notion of the “language-ready” brain, which is prewired for the cognitive system that enables language processing. In other words, there might be a biological basis for human language that is domain-specific, and this biological basis is unique to the human species.

Additionally, the “language-ready” brain theory suggests that the infant brain is prewired for language acquisition (e.g., Chomsky, 1957; Dehaene-Lambertz et al., 2002). Chomsky put forward arguments like: the rigid timetable of development (all children go through the same stages of acquisition, regardless of their culture), the efficiency of acquisition despite the poverty of the stimulus (poverty and variability of speech utterances to which children are exposed), the very early abilities of children to generalise grammatical rules, the apparent independence between language and intelligence (children with Williams syndrome, for example, develop a good command of language even though their intellectual capacities are reduced) and finally the universality of the development of the language faculty in all children (except for pathology) in all human societies (Chomsky, 1957/2009; Montant, 2021). Indeed, later studies have reported that all human infants seem to have an innate, inherited readiness for language acquisition, independently from culture. For instance, newborns are initially able to distinguish every phoneme before selectively discriminating only phonemes related to the language they are exposed to (Kuhl et al. 2008). During their first year, infants will be also sensitive to vocal sounds, their native prosody and vowels, infer the abstract structure of speech and connect words to their referents (Dehaene-Lambertz...
Therefore, this view of the evolution of language and the “language-ready” brain, follows a discontinuous or discrete logic (e.g., Hauser, Chomsky and Fitch, 2002; Berwick and Chomsky, 2016; Chomsky, 2017). In the evolutionary sense, it says that something mystical (perhaps a mutation) must have happened 100,000 to 75,000 years ago, when *Homo sapiens* appeared (or 350,000 years ago, since more recent studies dated *Homo sapiens* evolution earlier than previously thought: see Hublin et al., 2017; Richter et al., 2017).

The prewired and human-specific cognitive operation, which makes us understand and form grammatical sentences (“Theory of generative grammar” – Chomsky, 1965/2014) was further specified. In fact, as chomskyans explain, the emergence of the cognitive computation *merge*, gave rise to human-specific complex thoughts (e.g., Hauser, Chomsky and Fitch 2002, Chomsky, 2017). Merge recursively combines two basic syntactic objects into a new hierarchical higher order syntactic object, giving rise to “supra regular grammar” (Hauser and Fitch, 2004). Here, syntax is referring to the rules that combine elements and symbols to form phrases and sentences. Grammar is defined as the whole system and structure of a language (Chomsky, 1957/2009; 1965/2014).

Further, the recursivity of the merge operation generates an infinite quantity of sentences, based on a finite number of discrete units (Humboldt, 1836/1999; Hauser, Chomsky and Fitch, 2002). The merge computation is argued to be human specific, because supra regular grammar, which is based on “merge” has not been demonstrated in nonhuman primates (Hauser and Fitch, 2004).

Another, more general example in contemporary science, which follows the chomskyan logic was put forward by Friederici (Friederici, 2017). In her view, humans are unique in building and perceiving hierarchical sequences. Therefore, the emergence of language in humans is a direct consequence of this unique, syntactically similar ability (Friederici, 2017). However, in recent years, doubts rise for the incapacity of nonhuman primates to produce higher order grammars (Wang et al., 2015, Jiang et al., 2018, Fitch, 2018, Malassis et al., 2018; Malassis, 2020, Ferrigno et al., 2020). Note also, that in this point of view, the primary function for language is not communication (as part of externalisation) but the expression of thought (Chomsky, 2017, Fitch, 2020). In sum, this discontinuous view argues that the (unexplained) appearance of the basic cognitive operation “merge” gave rise to *Homo sapiens*, by enabling the processing of complex syntax for generating language. By definition in a phylogenetically view, the human species and in an ontogenically view, human infants, are prewired to be language-ready.

A second, very influential, line of discontinuous research is the approach of focusing on (peripheral) anatomical features that are supposed to be unique to humans. Lieberman et al (1969), for example, argued that humans are unique among primates in having a low larynx in their vocal tract and hypothesised that this might explain why humans are the only species that can speak because the low larynx allows vowel productions. In a long research project as an intern prior to the present PhD project, we investigated Lieberman’s theory, which until then had been the consensus. By
recording and analysing baboon vocalisations and modelling the baboon’s vowel space, we found that baboons were in fact capable of producing vowel-like sounds, despite their low laryngeal position (Boë et al., 2017; 2019; Kemp et al., 2017). We argued that it was not a change in peripheral anatomy that might have enabled language evolution, but rather a change in central neural connectivity (Boë et al., 2017; 2019). Therefore, my scientific interest shifted towards the brain (see later sections).

2.2. Continuous language evolution: A mosaic of domain-general functions

In recent years a view emerged that language may be the composite results of an assembly of cognitive properties that are domain-general and not specific to language (e.g., Fitch, 2010; Fedorenko, 2014; Christiansen and Chater, 2016; Fagot et al., 2019) (as opposed to language being one holistic language faculty). Therefore, language might also have emerged due to the co-evolution of several cognitive properties, rather than one only (Fitch, 2010, Fagot et al., 2019). As Tecumseh Fitch writes in his 2010 book “The evolution of Language”: “Language is not a monolithic whole, and from a biological perspective may be better seen as a “bag of tricks” pieced together via a process of evolutionary tinkering. To the extent that this multi-component perspective is correct, any attempt to single out just one aspect of language as “core” or “central” is a mistake.” And further: “The fact that humans, alone on our planet, have this particular capacity is no more surprising to evolutionary biologists than other unusual features like the elephant’s trunk, bat echolocation, or “radar” in electric fish. All of these “unique” traits, however, share components with other organisms, and language is no different.”

The rational for focusing on domain-general properties for understanding language evolution is based on the fact that language is a complex and phylogenetically recent ability. Therefore it most probably evolved from the reuse of components that where already present. To understanding this reasoning, one must first understand the evolutionary notion of exaptation (Gould and Vrba, 1982) that complements Darwin’s term adaptation. When, through natural selection, a species develops an anatomical structure over generations that performs a new function, that structure and its function are called adaptation (e.g., Plants that live in dry areas have adaptations to help them conserve water). Gould and Vbra proposed a complementary evolutionary mechanism to adaptation. Exaptation is not the result of natural selection, but an opportunistic selective adaptation, whereby new functions develop using traits related to older, initially selected functions. For example, flight in birds is a form of exaptation: flight is made possible by feathers, which were initially selected for their thermoregulatory function. An example of exaptation in humans concerns speech: the phonatory function was added to the main functions already in place, namely breathing or gustation (Montant, 2021).

In 2010, this function got reinterpreted by Anderson (Anderson, 2010), specifically concerning cognitive science. His concept of neural reuse explains that the same neural circuit can be permanently used and reused permanently for multiple functions.
during development and evolution without losing its original function. According to the massive redeployment hypothesis, most cognitive functions are based on widely reused neural circuits. This leads to two predictions: The first is that there should be a positive correlation between the phylogenetic age of a given brain region and the number of functions in which that region is involved (the older the region, the more frequently it is co-opted). Second, there should be a negative correlation between the age of a cognitive function and the number of brain regions it recruits (the older a function, the more localized it is). Both of these predictions are confirmed. Using a meta-analysis of data from 1469 fMRI studies, Anderson (2008) shows that the oldest (most posterior) regions are the ones activated in the most cognitive domains, and that the newest functions, such as language, recruit the greatest number of regions that are widely distributed across the cortical surface and extend into subcortical structures to piggyback its function on.

As an example of a domain-general cognitive function involved in language processes, we can take the cognitive and neuroanatomical overlap of language and memory (e.g. Roger et al., 2022), which is also thought to have interacted in the evolution of language (e.g. Fitch, 2010). In fact, syntax allows the hierarchical combination of symbols or verbal units to create complex structures (for more details, see section above). Complex syntax therefore requires a robust (phonological) memory system capable of flexibly organising and retaining the different verbal elements during online processing (Aboitiz et al., 2010). A reduced syntactic ability of nonhuman primate in comparison to human, could be explained by a reduced working memory capacity to hold communicative units on-line to create complex structures (Fitch, 2010; Fagot and De Lillo, 2011). Also on a neurophysiological level, Schomers et al. modelised that the human specific connectivity of the Arcuate Fasciculus, results in a shorter sensorimotor path length, which entails the emergence of verbal working memory,
Figure 2.4. – The images represent the co-activations of Brodmann areas for two different tasks in 1478 fMRI experiments. Black lines represent areas that are adjacent to each other, whereas orange lines represent non-adjacent to each other. Note the many black connections for the older function "action", while note the many orange lines for "language". In fact, "language" recruits more areas across the brain, making it the most widely distributed function of the areas examined in this study (Anderson, 2008) which in turn entails the emergence of language (Schomers et al., 2017).

Therefore, since nonhuman animals, especially primates, have been shown to share some of these “domain-general” cognitive properties, the research on nonhuman primates was reconsidered as a critical model to investigate language evolution (e.g., Fitch, 2010; Liebal et al., 2014; Fagot et al., 2019).

2.3. Ontogeny and Phylogeny as means to study language evolution

As stated in the last section, one of the rare ways to study language origins is by comparative inferences. I will here further explain why this comparison also extend to the development of nonhuman primates and our own species.

In the evolutionary logic, if we human have a certain cognitive trait and we find the same homologous trait in a close primate relative, then we can most probably infer that our last common ancestor also possessed this trait before our two species took different junction on their evolutionary road. Similarly, early newborn development is
thought to reflect traits shared with a more ancient common ancestor. Late development however reveals the species-specific traits. Already Darwin observed that wings of birds and legs of quadrupeds like cows are flagrantly similar at early embryonic periods and differentiates only progressively by fine steps (Darwin 1859/1964). With that observation he linked individual development with evolution along ancestral lines. Also, larvae of distantly related species resemble each other more than their mature selves. “Ontogeny recapitulates phylogeny” as stated by Ernst Haeckel (e.g., Levit and Hossfeld, 2019), implies therefore the repetition of evolutionary stages in the development of a single organism.

However, this memorable phrase of the Recapitulation Theory is not to be understood as a general rule and has received justified criticism. That ontogeny parallels phylogeny can maybe more accruable explained, for example, by Gregory Bateson as written in Mind and Nature, 1979, that the evolutionary selection after a genetic mutation is conservative. A mutation that affects the embryonic stage tends to be eradicated more quickly than a mutation that only takes effect later in the adult stage. The change that affects earlier in the life of the embryo must disrupt a longer and correspondingly more complex chain of later events. It is true that genes that are regulating early development are more conservative and phylogenetically more ancient with less variations than genes regulating later development. Thus, early genes and the expressed phenotypes are more likely to be shared between species in early stages of development. Thus, if we find shared morphological traits in early stages of development, they are of high probability predetermined by genetics and were shared with a common ancestor.

In fact, Niko Tinbergen named ontogeny as one the four rules/categories to explain a behaviour, together with Huxley’s causation, survival value and evolution (Tinbergen, 1963). He stressed that the change in the behavioural “machinery” during development must be distinguished from the change in behaviour during development. Therefore, one must distinguish between environmental influences that are affecting the animal, and those within the animal. In other words, in the category of ontogeny, the conclusion that a certain behavioural change is innate (or internally controlled) is only reached through elimination.

More generally, extensive work comparing human infants with human adults, as well as adult nonhuman primates with adult humans was undertaken. However little comparative work about the development of primate relatives was conducted, in order to join the ontogenetic and phylogenetic approach and to verify what is true about the recapitulation theory. That’s regrettable since several authors highlight the importance of a joint ontogenic and phylogenetic approach to understand human evolution. In fact, even modest changes in the involvement of regulatory genes in ontogenetic timing and plasticity may have considerable effects on the later phenotype. These changes are not directly encoded in the genes but emerges due to early interaction of an individual with the environment. Therefore, Michael Tomasello writes in his 2019 book “Becoming Human – A theory of Ontogeny”: “The implication is that if we wish to explain how uniquely human psychology is created, we must focus our attention on ontogeny, and especially on how great ape ontogeny in general has been transformed
into human ontogeny in particular (Tomasello, 2019)”. Similarly, Bard and Leavens (2014) plead for the consideration of compared development, across species in order to achieve a more accurate theory of primate (social) cognition (Bard and Leavens, 2014).

Furthermore, developmental nonhuman primate studies can serve as a model to investigate human brain development, as imaging studies on human infants are technically and ethically challenging (Song et al., 2021). Indeed, collecting longitudinal high-quality motion-free images from children below 4 years old is particularly difficult. In fact, recruiting and following the same homogenous infant cohort, motion artifacts and the reduction of scanning time to reduce this last, as well as unknown genetic and epigenetic influences are common challenges in human developmental studies. As a result, these challenges have limited our knowledge about brain development in this very dynamic and critical age range. Scanning nonhuman primate subjects, however, allows motion-free image collection at all age classes, thanks to close and careful anaesthesia monitoring. In addition, social and physical environmental factors as well as genetic and epigenetic mechanisms can be controlled or modified from conception into adulthood (Song et al., 2021).

This last point may clarify whether, when a common trait between humans and other nonhuman primate is discovered, its existence is present at birth and is thus genetically encoded, or whether it developed due to post-natal experiences. For example, studying the brain of developing monkeys can advance the question, whether (communicative) behaviour will shape its underlying brain structures, or whether the early brain development will shape later developing (communicative) behaviours.

### 2.4. Continuous or convergent evolution?

When the same cognitive properties are found between humans and nonhuman primates (see above), one catch arises: One cannot be certain, whether the results
are truly the results of a continuous evolution or rather the result of a convergent evolution (analogy). In fact, a convergent evolution can be defined as the independent appearance of similar features in species that are loosely related. This convergent evolution creates analogous structures that have similar forms or functions, but were not present in the last common ancestor of those species. A classic example is the independent evolution of flight in insects, birds and bats. Another example is the cephalopods eye, which has a chamber and a lens and resembles closely the human eye. However, the last common ancestor of us and octopuses is a flatworm that trawled the sea floor 750 million years ago and didn't possess any chamber-like eyes.

Figure 2.6. – An example for a convergent evolution: the cephalopod's eye. Note its similarity with the human eye.

Therefore, in order to clarify, if a shared cognitive function between humans and nonhuman primates is the results of a continuous or convergent evolution, we can compare their respective underlying structure: the brain.

2.5. The model: the baboon brain

The olive baboon (Papio anubis) is a suitable model in this quest, due to its phylogenetic proximity to humans, its similar “Umwelt” (e.g., Uexküll, 1909/Mildenberger and Herrmann, 2014) and its gyrified brain. In fact, the baboon is a representative of the Old world monkey family, with which we share a common ancestor who lived roughly 25-35 millions years ago (Stevens et al., 2013). The species of olive baboon is named after its grey-greenish looking fur from the distance. Its Latin name Papio anubis, comes from its dog-like muzzle that reminded of the Egyptian god Anubis, represented by a dog head. Due to sexual dysmorphism, its length can range from 50 to 114 cm and a weight of 10 to 37 kg, with males being longer and heavier. This species is terrestrial and inhabits large parts of central Africa, which are mostly grasslands.
Regarding the social structure, olive baboons live in multi-male, multi-female groups with lesser males than females. Female dominance is hereditary with daughters ranking similarly to mothers and forms the core of the social organisation. Males on the contrary, leave the parental group at sexual maturity and join a next group, where they compete for their dominance more violently than females. However, not only strength but also alliances, coalition, and approbation from females, help males to rise in the hierarchy. All information: Cawthon Lang, 2006. Primate Factsheets: Olive baboon (Papio anubis) Taxonomy, Morphology, and Ecology*, see Wisconsin National Primate Research Center, Primate Info Net). Despite being hierarchical, collective decision are agreed on for the direction of collective movements (e.g., Strandburg-Peshkin et al., 2015).

Newborns have a black coat at birth with bright pink skin. In its first days, the infants develop sufficient grasping force to hold to the mother’s fur. In the next weeks it stays close to the mother with increasingly longer distances of exploring. Approximately by eight months, the infant is weaned and feeds on an omnivorous diet. However, this age varies depending on the hierarchy of the mother, with higher ranked mothers being more relax and weaning earlier their offspring and lower ranked mother keeping their offspring longer close to them. Females are sexually mature by the age of 4, males by the age of 5.

Figure 2.7. – Olive baboons at the CNRS, Station de Primatologie, Rousset

In the beginning of the last century, the baboon was massively imported to France from its former colonies to advance medical research. A result of this history constitutes the UAR846 CNRS Primate Station in Rousset-sur-Arc, France, which elevates monkey species for research institutes worldwide. The individuals are kept in enclo-
sures or cages, with ethological enrichments and several feedings per day. Whereas it would be more suitable to compare baboon brains and behaviour in natural ecological conditions, the UAR846 CNRS Primate Station presents the unique opportunity of studying longitudinal brain and behaviour development. In fact, the station’s geographical proximity to the fMRI centre in Marseille allows the transport from and to the scanner in a same day.

Baboons, in particular, are a promising model for understanding the evolution and pathologies of human brain organisation (e.g., Black et al., 2011; Fagot et al., 2019). In contrast to the macaque brain, which is the common model of Old world monkeys in neuroscience, the baboon brain possess a higher degree of gyrification (Leigh et al., 2004) and has in average a two times larger brain volume (Rogers et al., 2010). Consequently, it was used in numerous MRI studies (eg., Kochunov et al., 2010a, 2010b; Kroenke et al., 2005, 2007; Wey et al., 2013 ; Love et al 2016) and additionally constitutes a distinguished model for epilepsy (Killam, 1979; Szabo et al., 2012).

Concerning cerebral development of baboons, little is known. Some knowledge comes from work in macaques that have shown that volume of grey matter decreases while white matter increases in monkeys during late infancy, earlier than for a proportional age in humans and regionally specifically. The more complex and extended brain development in humans permits a longer influence of postnatal experiences on the brain architecture (Liu et al., 2015). In fact, the frontal and temporal lobes showed the largest postnatal increase in volume during the first year with a peak of synapse density around 3 months with synapse pruning happening afterwards (Scott et al., 2016). Because of the immature brains of the newborn subjects, T2w MRI signal may be more suitable than T1w MRI signal for manual delineation for the first longitudinal scans. In fact, the T2w MRI signal is sensitive to the free water present in voxels. The proliferation of membranes due to synaptogenesis and the process of myelination will decrease the proportion of free water in the gray matter voxels and thus darken the images during maturation of the first human year post-natal. Therefore, a higher contrast is generated in T2w images in comparison to T1w images in early immature
brains, which helps for better delimitation and segmentation (for human newborns see: Dehaene-Lambertz and Spelke, 2015).

Figure 2.9. – T1w coronal image of an averaged baboon brain shortly after birth (left) and at 8 months of age (right). Note the contrast inversion between both scans in the temporal lobe.

2.6. Perisylvian brain organisation

2.6.1. Large scale primate brain databanks

Comparative brain approaches for primate species have particularly focused on neuroanatomy, given the well-known limitation for functional studies in apes and monkeys (e.g., techniques, ethics, sample size, reproductivity). The advent of non-invasive techniques such as Magnetic Resonance Imaging (MRI) favours in-vivo acquisitions, on anesthetised subjects, allowing no limitation in terms of sample sizes and species diversity (e.g., Poirier et al., 2021). As a result, primate brain research has benefited in the recent year from considerable increase of available MRI databases on large cohorts in many primate species, including macaques: Prime-De, (Milham et al., 2020) and chimpanzees: www.chimpanzeebrain.org (e.g., Hopkins et al., 2008). Regarding development, part of my supervisor's Adrien Meguerditchian ERC project “GestImage”, aims to collect the cerebral development of 30 newborn baboons and on which study 1, 2 and 3 are based in the present thesis. Note also Adrien Meguerditchian's precedent project “LangPrimate”, in which MRI scans of adult baboon brains (n: 100) were collected and on which study 4 is based in this thesis.

2.6.2. Language brain lateralisation

In humans, language models congruently describe a few key hubs of language processing, namely Broca's and Wernicke's area, and their interconnection, the Arcuate Fasciculus (Geschwind, 1970; Toga and Thompson, 2003; Bidula and Krolczak, 2015; Becker et al., 2022b - the fifth contribution of this thesis). However, in recent years, data are expanding to more distributed models, taking into account several different fibre tracts and regions crucial for language processing as demonstrated by clinical
cases (e.g., Catani and Mesulam, 2008) and questioning a localisationist viewpoint of language specialisation (e.g., Duffau et al., 2018). For example, the importance of regions in the interface between social cognition and communication like the Superior Temporal Sulcus and Geschwind’s territory in the Inferior Parietal Lobe are highlighted (Catani and Dawson, 2017), as well as the anterior Insula cortex and the anterior and mid-Cingulate Sulcus. Most of these structures share one fundamental feature: They are functionally and also structurally specialised towards one hemisphere, mostly the left (Toga and Thompson, 2003; Keller et al., 2011; Amiez et al., 2019). Specifically, "functional lateralisation" refers to a more pronounced activation in one hemisphere than the other. "Structural lateralisation" refers to a more pronounced volume, size, surface measurements or neuron density of a given region in one hemisphere than the other. Although the link between structural and functional asymmetry remains in question (e.g., Gerrits et al., 2021; Tzourio-Mazoyer et al., 2018), most authors usually consider that structural asymmetry (“the size of the roads”) of these regions might reflect the functional asymmetry (“the traffic”) for language tasks (Dehaene-Lambertz et al., 2002; Catani et al., 2007; Keller et al., 2011). Interestingly, within an evolutionary framework, hemispheric specialisation has been historically considered unique to human language evolution (Crow, 2004; Warren, 1980).

But how and why became the brain asymmetric in the first place? Prominent theories state that in primate evolution, cortical volume (neurons) expanded faster than interhemispheric corpus callosum connections fibres (axons) leading to specialised regions in hemispheres with one hemisphere dominant over the other. Indeed, evolution favours the most efficient neural network. Fewer direct connections between hemispheres and an increased transmission delay of the signal, due to a larger distance between hemispheres in bigger brains, may have favoured faster intra hemispheric communication for routine tasks. Changes like this are supposed to have increased regional asymmetry (Ringo et al., 1994, Rilling and Insel 1999, Atkinson et al., 2016; Hopkins et al., 2015; Ocklenburg, 2012). In addition, these changes helped also to increase one’s ability to perform several tasks at the same time (Rogers et al., 2004; Ocklenburg, 2012), and increased neural efficiency, thanks to the reduction of duplicated neural networks (Vallortigara and Rogers, 2005; Ocklenburg, 2012). This theory is also used to explain the dominance of the left hemisphere for language processing in the human brain. An open question remains, why especially the left and not the right hemisphere has specialised for language processing. Some argue that the left superior temporal gyrus functions is more capable of integrating information over a shorter timescale (Albouy et al., 2020), due to an underlying higher synaptic density than in the right hemisphere (Neophytou et al., 2021).

### 2.6.3. Interlude

In the next sections I aim to review the literature comparing structural brain asymmetries across primates for areas related to language in humans. We will focus on the classical perisylvian language regions, namely the Planum Temporale, Broca’s Area and the white matter tract that interconnects these two regions: The Arcuate Fasci-
culus. After briefly describing their functions, I will first review their structural and functional lateralisation in humans, including infants, to discuss whether structural markers can predict the functional lateralisation of language. In a next step I will compare these findings with nonhuman primates and discuss whether this asymmetric organisation is shared between species. Because, just as in human brain research, research on primate brain anatomy allows morphological quantification of regions in each hemisphere and determine possible interhemispheric asymmetries.

### 2.6.4. Planum Temporale

The most emblematic marker of the lateralised language organisation is the Planum Temporale (PT) which is located within the Sylvian fissure and which is part of the auditory association cortex (Galaburda et al., 1978) and Wernicke’s area (Mesulam et al., 1998). In adults, left hemispheric lesion of this region resulted in severe language comprehension and production deficits (Wernicke, 1874; Dronkers et al., 2004; Borovsky et al., 2007). Therefore, many studies have shown the particular functional significance of the PT in the left hemisphere in a variety of auditory language processing (Shapleske et al., 1999), including the main perception component of the audio-motor loop for phonological processing (Vigneau et al., 2006).

Interestingly, also in preverbal newborns the functional implication of the left PT was highlighted from birth on (Dehaene Lambertz et al., 2002; 2010; Mahmoudzadeh...
et al., 2013). In the pioneering work of Geschwind and Levitsky (1968) the PT was shown to be anatomically asymmetric: In 100 post-mortem brains, 65 % of the left PT was larger than the right, which was confirmed by in-vivo MRI studies (Shapleske et al., 1999) and also highlighted in early development (Post-mortem Infants: Wada, 1975; Witelson et al., 1973. In-vivo MRI infants: Dubois et al., 2008; 2010; Glasel et al., 2011; Hill et al., 2010; foetuses: Chi et al., 1977a;b). These asymmetries are later increasing during development, which was associated with language development (Wada, 1975; Dehaene-Lambertz et al., 2002; 2010; Mahmoudzadeh et al., 2013). The PT asymmetry is therefore seen a marker for the human unique innate readiness to acquire language (e.g., Dehaene-Lambertz et al., 2002). Indeed, in adults a direct relationship was shown between the left PT’s size and functional asymmetry of language tasks (Josse et al., 2003; 2006). In addition, an absence or reversed PT asymmetry has been linked to several language related pathologies like dyslexia (Gauger et al., 1997; Altarelli et al., 2014). This function-structure relationship is however debated (Jäncke et al., Steinmetz, 1994; Dorsaint-Pierre et al., 2006; Eckert et al., 2006; Keller et al., 2011; Greve et al., 2013; Kolinsky et al., 2014; Tzourio-Mazoyer and Mazower, 2017; Tzourio-Mazoyer, Crivello and Mazoyer 2018; Ocklenburg et al., 2018; Gerrits et al., 2021). For example, Greve et al. (2013) showed that regardless of the functional hemispheric dominance for language, the structural PT volume asymmetry is left biased. In contrast, Ocklenburg et al. (2018) found that a higher density at a microstructural level of the left PT was associated with faster processing of auditory speed in the same area, as shown in EEG. More recently, Tzourio-Mazoyer et al. (2018) demonstrated that, although the structural PT asymmetry is not predictive of its functional counterpart in a language task, an adjacent auditory area at the end of the Sylvian fissure is.
Several studies in nonhuman primates also showed striking human-like PT asymmetries in their homologous regions. Manual delineation of post-mortem brains (Gannon et al., 1998), in-vivo MRI scans (Hopkins et al., 1998; Hopkins and Nir, 2010) as well as voxel-based morphology on MRI scans (Hopkins et al., 2008), showed larger left PTs in chimpanzees and in apes in general (Cantalupo et al., 2003). A potential candidate related to such a function may be communicative gesture. Indeed, Meguerditchian et al. (2012) highlighted a relation between Planum Temporale grey matter volume asymmetry and hand preference for communicative gesture in chimpanzees. Moreover, the left PT asymmetry was also found related to handedness for tool-use but not for handedness for manipulative actions in chimpanzees (Gilissen and Hopkins, 2013).

2.6.5. Broca’s area

Broca’s area (BA44, BA45) and its left hemispheric specialisation was historically considered as the centre of speech production (Broca, 1861). This modular view of the neural basis of language was progressively questioned by the view that language involves a plastic and large distributed network (Hickok and Poeppel, 2007; Duffau et al., 2018) and even implicates the two hemispheres. However, it is still well acknowledged that Broca’s area in the left hemisphere remains a key knot for language specialisation within its distributed neural network (e.g., Friederici, 2017). Interestingly, complementary work thereby highlighted Broca’s area as lateralised interface between speech and multimodal motor integration including gesture and mouth movements (e.g., Gentilucci and Volta, 2008). Broca’s area is also known for its involvement in motor planning, sequential and hierarchical organisation of behaviours, including syntax.

Figure 2.12. – Illustration of the Broca’s area (in red) in the human brain. Source unknown
tool-use (Stout and Hecht, 2017) and sign language production including thus manual and oro-facial gestures (Emmorey et al., 2004; Campbell, MacSweeney, and Waters, 2008).

In infants, speech perception activates Broca’s area from very early development on as highlighted in MEG or functional MRI studies (e.g., Imada et al., 2006; Dehaene-Lambertz et al., 2006; 2010). This activation before the babbling stage suggested that activity of this area is not due to motor learning but might drive learning of complex sequences (Dehaene-Lambertz et al., 2006).

In contrast to the PT (see section above), a clear structural leftward asymmetry has not been reproducibly demonstrated (Keller et al., 2009; Sprung-Much et al., 2021), which may be due to natural variability between subjects in sulcal contours defining this area (Keller et al., 2007; 2009). Cytoarchitectonic analyses however reported a leftward asymmetry of some parts of area 44 and/or area 45, which together form Broca’s area (Scheibel, 1984; Amunts et al., 1999; 2003). In contrast, other accounts state a rightward asymmetry for area 45 grey matter, which gets reduced during aging, especially due to a loss in the right hemisphere (Kurth et al., 2020). In development, an early structural primacy of right-sided dendrite systems shortly after birth and a progressive shift to left-sided primacy during years 3 to 6 was highlighted and related to critical periods for language acquisition (Simonds and Scheibel, 1989). A second study found leftward asymmetries on the cellular level very early from 1-year old infants on (Amunts et al., 2003), which increased into an adult-like leftward asymmetry at 5 years for area 45 and 11 years for area 44. This maturational effect was suggested to be influenced by language practice and thus, the interhemispheric asymmetry of this area would continue to change throughout life (Amunts et al., 2003). Interestingly, because area 45 supports semantic processes and area 44 subserves syntactic processes in adults, some see in this maturational difference a neural underpinning of the earlier onset of semantics than syntax in children (Friederici, 2017).

In great apes, a homologous region was documented in several studies, which described the precentral inferior sulcus, the inferior frontal sulcus and the fronto-orbital sulcus as common borders of Broca’s homologue (e.g., Cantalupo and Hopkins, 2001; Keller et al., 2011; Hopkins, 2017). Like in humans, inquiries about Broca’s area’s structural asymmetry on a population-level remain inconsistent in apes, due to interindividual variation in location and cytoarchitecture (Schenker et al., 2010). Leftward lateralisation was found at a macrostructural level (Cantalupo and Hopkins, 2001) but not at a cytoarchitectonic level in a relative smaller sample-size (Schenker et al., 2010; but see also Graic et al., 2020).

In monkeys, no data of structural asymmetry for this region has been reported so far. In fact, determining Broca’s homologue is challenging, because the common borders of Broca’s homologue in apes are absent in monkeys. Nevertheless, we know from few detailed cytoarchitectonic studies in macaques, that the two parts of Broca’s area 44 and 45, are respectively located in the fundus and lower caudal/posterior bank-, and on the rostral/anterior side, of the most ventral part of the Inferior Arcuate Sulcus (IAS) (Petrides et al., 2005; Petrides, 2005; Belmalih et al., 2009). Electric stimulation of this region elicited oro-facial and finger movements. Therefore, together with
cytoarchitectonic similarities, the region anterior to the ventral part of the IAS was proposed as an equivalent area 44 in macaques (Petrides, 2005). Recent studies even reported that Broca’s homologue's activation preceded voluntary trained production of a vocalisation after intensive operant conditioning in juvenile rhesus monkeys (Hage and Nieder, 2013). Moreover, the use of positron emission tomography (PET) in 3 captive chimpanzees has revealed that begging food from a human by using either gestures, atypical attention-getting sounds, or both of them simultaneously, activated a homologous region of Broca’s area (IFG) predominantly in the left hemisphere (Taglialatela et al., 2008).

Figure 2.13. – The inferior arcuate sulcus/Broca’s homologue (in red) in the vertex of an adult baboon brain, BrainVisa software.

Some functions associated to Broca’s homologue’s lateralisation in nonhuman primates have been proposed in relation to tool-use processing and communication gesture production. Regarding tool-use, chimpanzees that performed better a tool-use task with their right hand showed a greater left-lateralisation of Broca’s homologue (Hopkins et al., 2017). Such a link might be attributed to the typical Broca’s function described in humans, namely hierarchical organisation of behaviours involved in tool-use (e.g., Koechlin and Jubault, 2006; Stout and Hecht, 2017). Regarding gestural communication, Meguerditchian et al., (2012) highlighted a relation between Broca’s homologue grey matter volume asymmetry and hand preference for communicative gesture in chimpanzees.

2.6.6. Arcuate Fasciculus

The Arcuate Fasciculus (AF) is a bundle of white matter, which arches dorsally around the Sylvian fissure, interconnecting Broca’s area in the frontal lobe with the Planum Temporale in the temporal lobe (e.g., Catani and Thiebaut de Schotten, 2012). It was highlighted that the connectivity between language areas, due to the AF, is crucial. For example, the integrity of the AF might be more important for lesion
recovery (e.g., strokes) than the integrity of grey matter regions that it is connecting (e.g., Duffau, 2018). In addition, as neurological cases have shown, the AF plays a key role in language processing in the left hemisphere, with lesion of the direct pathway causing conduction aphasia (e.g., Catani and Mesulam, 2008), also in deaf signers (Metellus et al., 2017). The AF is already present at birth (Dubois et al., 2016) but matures slowly until late childhood (Brauer et al., 2013, Dubois et al., 2016).

Figure 2.14. – Liberal tractography result for the Arcuate Fasciculus (Yeh et al., 2018).

In contemporary language models, the AF (or also called "Dorsal Pathway") is often opposed to the "Ventral Pathway", which interconnects roughly the same regions, but travels ventrally around the Sylvian fissure (Hickok and Poeppel, 2004).

In contrast to the AF the "Ventral Pathway" matures more rapidly in development and was also described to be phylogenetically more ancient (e.g., Brauer et al., 2013; Friederici, 2017). The late maturing of the AF is proposed to be due to the frontal portion, which connects to Broca's area and is only fully myelinated by the age of 7 (Brauer et al., 2011; Brauer et al., 2013). In fact, controversy persists whether this portion is also already present at birth (Dubois et al., 2006; 2009; 2016; Perani et al., 2011; Friederici, 2012).

Regarding lateralisation, the human AF was shown larger in the left hemisphere for a number of macroscopic and microscopic measurements like the number of streamlines, volume of the tract, fibre density and mean fractional anisotropy in 60 Percent of normal adult humans. The remaining 40 % of the adult population shows either a reduced lateralisation to the left (20 %) or not lateralisation at all (20 %) (Büchel et al., 2004, Nucifora et al., 2005, Powell et al., 2006; Catani et al., 2007; Thiebaut de
Schotten et al., 2011; Takaya et al., 2015). In early development, the leftward AF is the most asymmetrical region of the developing white matter (Dubois et al. 2009; Liu et al., 2010, but see also Song et al., 2015).

Interestingly, the early leftward asymmetry in newborns was correlated with later language capacities in children (Lebel and Beaulieu, 2009; Lopez-Barroso et al., 2013; Salvan et al., 2017). Catani et al., (2007) argued that the AF's asymmetry represents a better structural marker for functional language specialisation than the Planum Temporale asymmetry (Catani et al., 2007). This structure-function relationship is however debated (Propper et al., 2010; Zhu et al., 2014; Silva and Citterio, 2017; Gerrits et al., 2021; Verhelst et al., 2021). For example, Verhelst et al. (2021) demonstrated in a fixel based analysis, that the structural AF asymmetry did not differ between subjects with either right or left functional language hemispheric dominance.

Axon tracing in monkey brains and diffusion MRI in chimpanzee and monkey brains have highlighted the existence of the Arcuate Fasciculus across primates that interconnects frontal and temporal areas (Schmahmann and Pandya, 2006; Petrides and Pandya, 2009; Petrides, 2014; Rilling et al., 2008, Rilling et al., 2011; Frey et al., 2014; Eichert et al., 2019; Barrett et al., 2020; Balezeau et al., 2020; Rocchi et al., 2021). In order to highlight anatomical differences across primates, which could explain the human uniqueness for language, several authors conclude that the left AF lateralisation is the crux of the human-specific distinction (Eichert et al., 2019; Balezeau et al., 2020; Rocchi et al., 2021). In fact, Rilling et al. (2008) did not find any AF asymmetry in three macaque and four chimpanzee subjects. However, by adding more chimpanzee subjects, the authors were able to report a left lateralised AF, which was still weaker than in humans (Rilling et al., 2012). This result remained unique regarding AF lateralisation in nonhuman primates (Eichert et al., 2019, Balezeau et al., 2020; Rocchi et al., 2021). In fact, this inconsistency across the literature about the presence or absence of population-level leftward AF bias might be explained by the small sample size (i.e., only few subjects) usually included in those AF studies in apes, which makes difficult to infer any bias at population-level. Only studies including an increased sample size of subjects would help elucidate this debate.

### 2.6.7. Function of language lateralisation?

In humans, handedness for manual actions was for a long time considered as such a behavioural reflection of a language related brain lateralisation (e.g., Knecht et al., 2000). However, more recent studies indicate that direction of handedness for manual actions poorly predicts language lateralisation, especially in left-handed humans. Indeed, 96% of right-handers and also 70% of left-handers have their left hemisphere functionally specialised for most language functions (e.g., Knecht et al., 2000). In fact, handedness for manual actions was shown to be associated to the contralateral lateralisation of the motor hand area within the Central Sulcus, rather than key language areas (Amunts et al., 2000). Altogether, it is now acknowledged that direction of handedness might be independent from direction of language lateralisation (Groen et al., 2013; Mazoyer et al., 2014; Ocklenburg et al., 2014). As a result, comparative
research on handedness for manual actions across primates might not be suitable for investigating phylogenetical origins of hemispheric language specialisation.

Figure 2.15. – Juvenile baboon doing the "Handslap", an example for communicative gesture in monkeys (Meguerditchian and Vauclair, 2008).

To do so, it has been suggested that studying manual lateralisation of gestural communication in nonhuman primates - and not handedness for manipulative actions - might constitute a more fruitful approach (e.g., Meguerditchian et al., 2013). In fact, following the evolutionary framework about the gestural origins of language (e.g., Hewes, 1973), the gestural communication system in nonhuman primates was found to share key features of domain general processes, important for language, such as intentionality, referentiality and learning flexibility (e.g., Tomasello, 2008; Meguerditchian and Vauclair, 2014; Molesti et al., 2020). Interestingly, production of communicative manual gestures has been found highly lateralised in favour of the right-hand in both baboons and chimpanzees. In contrast, the handedness patterns for non-communicative manual actions in chimpanzees and baboons were found to be different from those found for communicative gestures at both the populational but also the individual level (Meguerditchian et al., 2013). These findings supported the idea that gestural communication in nonhuman primates may be related to a specific lateralised system for communication, which might be different than handedness for manipulative actions (Meguerditchian and Vauclair, 2014).

2.7. Overview of my research contribution

In the sections above, I have reviewed the functions and the structural and functional lateralisation of the main perisylvian language network (Broca’s area, Planum Temporale, Arcuate Fasciculus) in humans including infants. I have also compared the data with findings from nonhuman primates (mainly apes) and discussed whether this asymmetric organisation is shared between species. Several questions remain however unanswered:
1. Is a lateralised perisylvian organisation shared beyond humans and apes, but with Old world monkeys?

2. When does such an asymmetric organisation appear in development and will it predict later behaviours?

3. If such brain lateralisation is shared with our non-linguistic primate cousins, for what behavioural functions did it evolve, if not for language?

In an attempt to give some elements of responses, I present the following five studies that we have conducted:

1. In my first study we showed that the Planum Temporale already present a larger left-than-right surface asymmetry in a majority of subjects at birth, a key characteristic of the cerebral development of language. In addition, its asymmetry strength was found increasing with age, similarly to human infants.

2. In my second study, we have replicated this finding of early Planum Temporale asymmetries based on grey matter volume measurement.

3. In my third study, we investigated whether this early asymmetry predicts later development for gestural communication handedness. Indeed, the baboons that showed a larger left Planum Temporale at birth, became more likely right-handed in communication than those that had an equal or larger right Planum Temporale. No effect was found for non-communicative actions.

4. These results are in line with my fourth study that concerned adult baboons and Broca’s homologue. We found that the depth of the ventral section of the inferior arcuate sulcus (a marker of Broca’s homologue) showed an inter-hemispheric asymmetry that was associated with contralateral handedness for communicative gesture, but not with handedness for non-communicative, manipulative actions. In other words, those baboons that are communicating with their right hand have the Broca homologue deeper in the left hemisphere and vice versa.

5. Finally, the Arcuate Fasciculus’ evolutionary morphology change is at the base for major theories about language evolution. However, via an extensive review I highlighted in my fifth contribution, that based on new techniques, the Arcuate Fasciculus is more similar than previously thought between primates. An open question remains, whether its lateralisation differs between human and non-human primates and whether it is linked to gestural communication.
3. Chapter: Early Left-Planum Temporale Asymmetry in Newborn Monkeys (*Papio anubis*): A longitudinal structural MRI study at two stages of development

Published article:

Early Left-Planum Temporale Asymmetry in newborn monkeys (Papio anubis): A longitudinal structural MRI study at two stages of development

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A R T I C L E   I N F O

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A B S T R A C T

The “language-ready” brain theory suggests that the infant brain is pre-wired for language acquisition prior to language exposure. As a potential brain marker of such a language readiness, a leftward structural brain asymmetry was found in human infants for the Planum Temporale (PT), which overlaps with Wernicke’s area. In the present longitudinal in vivo MRI study conducted in 35 newborn monkeys (Papio anubis), we found a similar leftward PT surface asymmetry. Follow-up rescanning sessions on 29 juvenile baboons at 7-10 months showed that such an asymmetry increases across the two ages classes. These original findings in non-linguistic primate infants strongly question the idea that the early PT asymmetry constitutes a human infant-specific marker for language development. Such a shared early perisylvian organization provides additional support that PT asymmetry might be related to a lateralized system inherited from our last common ancestor with Old-World monkeys at least 25-35 million years ago.

1. Introduction

Language and its typical functional and structural asymmetric brain organization were initially considered as unique to Homo sapiens evolution (Crow, 2004), suggesting a specific “language-ready” brain dating back to 350 000 years ago. Therefore, brain lateralization in several regions was hypothesized as one of the key features of the language-ready brain, as most humans show a greater cortical activation in the left hemisphere for most language functions (Vigneau et al., 2006). For instance, the left Planum Temporale (PT) area which overlaps with Wernicke’s area was found particularly activated in a variety of auditory language processing tasks like phonological auditory decoding (Shapleske et al., 1999) and including the main perception component of the audio-motor loop for phonological processing (Vigneau et al., 2006). In the pioneering work of Geschwind and Levitsky (1968), a leftward PT asymmetry was also found at the anatomical level, suggesting its relationship with functional brain asymmetry for language tasks (Jose et al., 2006; Tzourio-Mazoyer et al., 2019).

Additionally, the “language-ready” brain theory suggests that the infant brain is pre-wired for language acquisition (e.g. Dehaene-Lambertz et al., 2002). Indeed, studies have reported that all human infants seem to have an innate, inherited readiness for language acquisition, independently from culture. For instance, newborns are initially able to distinguish every phoneme before selectively discriminating only phonemes related to the language they are exposed to Kuhl et al. (2008).

During their first year, infants will be also sensitive to vocal sounds, their native prosody and vowels, infer the abstract structure of speech and connect words to their referents (Dehaene-Lambertz and Spelke, 2015).

The neural structure for such a language readiness remains unclear. Nevertheless, white and grey matter organization in infants reveals similar architecture in comparison with adults (Dubois et al., 2010). Interestingly, similar to adults, three-month-old infants’ BOLD responses to speech showed a more pronounced activation of the PT in the left hemisphere (Dehaene-Lambertz et al., 2002), raising the question whether or not the PT might be functionally lateralized from birth on. Addition-
ally, structural PT leftward asymmetry was also shown in post-mortem fetuses or infant brains in early development (Witelson and Pallie, 1973; Wada, 1975; Chi et al., 1977) and with in-vivo structural MRI images (Dubois et al., 2010; Hill et al., 2015; Glisè et al., 2011). Such a structural PT left asymmetry may be stabilized during the last trimester of fetal life (Chi et al., 1977) and are later increasing during development, suggesting its links with language development (Chi et al., 1977).

However, several studies in nonhuman primates questioned the structural PT asymmetry as a human-specific marker for the brain specialization for language. Manual delineation of post-mortem brain (Gannon et al., 1998) and in-vivo MRI scans (Hopkins et al., 1998; Hopkins and Nir, 2010; Marie et al., 2018), showed larger left PTs in both apes and baboons, suggesting that this neuroanatomical feature is shared also with Old-World monkeys.

Whether such an early neuroanatomical feature extended to other nonhuman primate infants is unknown although this comparative question remains critical for determining its supposed human uniqueness trough evolution and its relation to a pre-wired brain for language acquisition.

Therefore, the aim of the present longitudinal in-vivo MRI study in nonhuman primates is to investigate, the structural neuroanatomical PT asymmetries in 25 baboon infants (Papio anubis) and its development across age through manual delineation of the region's surface. The earliest post-natal age class includes 33 newborns at the critical neurodevelopmental period below 3 months (as well as two 5-months old outliers) in which the synaptogenesis is maximal and the myelin, synapses and cell bodies are thus not fully mature (Scott et al., 2016). The follow-up MRI longitudinal scanning and PT delineation includes 29 of those 35 baboons at the older juvenile age class (i.e., from 7 to 10 months).

2. Methods

2.1. Subjects

Subjects ranged from 4 to 165 days of age (Mean: 32.63; SD: 6.13) and included 21 males and 14 females. Out of those 35 baboons, 29 were later rescanned a second time, ranging from 218 to 362 days of age (Mean = 278.62; SD = 30.11) (see table in supplementary methods with subjects’ details).

All monkeys are housed in social groups at the Station de Primatologie CNRS (UPS 846, Rousset, France) and have free access to outdoor areas connected to indoor areas. All subjects are born in captivity from F1 or 2 generations (F2). Wooden and metallic structures enrich the enclosures. Feeding times are held four times a day with seeds, monkey pellets and fresh fruits and vegetables. Water is available ad libitum.

2.2. Animal handling

Minimally invasive medication was realized, and no premedication was needed. Mothers from the newborn subjects were captured with their infant the night before the scan at the Station de Primatologie for check-ups and were transported together the following day of the MRI session.

Upon arrival at the MRI center, the mother of the focal subject was sedated with an intramuscular injection of ketamine (3mg/kg) and medetomidine (30 μg/Kg) as well as their focal infant if above 5 months old. Focal newborn below 5 months were not sedated and directly brought to the preparation room for the following procedures. Focal infants were then anesthetized under 6-8% sevoflurane induction with a mask. A catheter was then inserted into the caudal artery for blood-gas sampling, and tracheal intubation was performed for steady controlled ventilation using an anesthetic ventilator (Cato, Drager, Germany). End-tidal carbon dioxide was monitored and used to adjust ventilation rate (0.2 to 0.3 Hz) and end-tidal volume. The anesthesia inside the MRI machine was then maintained using 3% sevoflurane via a calibrated vaporizer with a mixture of air 0.75 L/min and O₂ 0.1 L/min). Peripheral oxygen saturation, heart rate and breathing rate, were monitored throughout experiments.

All animal procedures were approved by the “C2EA - 71 Ethical Committee of neurosciences” (INT Marseille) under the number APAFIS#13555-201802151547792 v4, and has been conducted at the Station de Primatologie under the number agreement C130877 for conducting experiments on vertebrate animals (Rousset-Sur-Arc, France). All methods were performed in accordance with the relevant French laws (CNRS guidelines and the European Union regulations (Directive 2010/63/EU)).

2.2.1. Imaging protocol

From September 2017 to March 2020, in-vivo imaging was performed using a 3T clinical MRI scanner (MAGNETOM Prisma, Siemens, Erlangen, Germany) equipped with 80 mT/m gradients (X: 80/200 gradient system with slew rate 200 T/m/s) and a 2-channel B1 transmit array (TimTX TrueForm). For the sessions at t0 (“newborn” age class) and at t1 (i.e., from 7 to 10 months old), the animals were scanned in the supine position, with two 11 cm receive-only loop coils: one under the head and another one around the face of the animal. The holding of the two coils and the animal head was provided through the use of a pearl-tec bag (Vac Fix System) and some straps. Protection for noise reduction was attached around the ears. At the end of the MRI session, when fully awakened from anesthesia, baboons were carefully put back with their mother and then transported back at the Station de Primatologie for immediate (or delayed) reintroduction into their social groups under staff monitoring.

2.2.2. Structural acquisition protocol

T1w images were acquired using a 3D Magnetization Prepared Rapid Acquisition Gradient Echo (MPRAGE) (Mugler and Brooks- man, 1999) sequence (0.4 mm isotropic, FOV = 103 × 103 × 102.4 mm, matrix=256 × 256 slices per slab=256, sagittal orientation, read-out direction of inferior (I) to superior (S), phase oversampling = 10%, averages=3, TR = 2500 ms, TE = 3.01 ms, flip-angle = 8°, bandwidth=300 Hz/pixel, no fat suppression, pre-scan normalization). T2w images were acquired using a Sampling Perfection with Application optimized Contrast using different angle Evolutions (SPACE) sequence (Mugler et al., 2000) (0.4 mm isotropic, FOV = 154 × 115.5 × 102.4 mm, matrix=384 × 288, slice per slab=256, sagittal orientation, read-out direction I to S, phase oversampling=0%, averages=2, TR = 3200 ms, TE = 393 ms, bandwidth = 566 Hz/pixel, no fat suppression, echo train length = 790 ms and pre-scan normalization). The total acquisition time for structural scans was 65 min (35 min for T1w and 30 min for T2w).

2.3. Preprocessing of anatomical MRI

Anatomical T2w images of the first scanning session and anatomical T1w images of the second scanning session were noise corrected with the spatially adaptive nonlocal means denoising filter (Manjón et al., 2010) implemented in Cat12 toolbox (<http://www.neuro.uni-jena.de/cat/> included in SPM12 (<http://www.fil.ion.ucl.ac.uk/>), which runs on MAT-LAB (R2014a).

Next, each image was manually oriented using ITK-Snap 3.6 according anterior and posterior commissures plane and the interhemispheric fissure plane.

2.4. Manual delineation of the PT

Manual delineation of the PT in the present study followed the same procedure as the previous MRI study on the PT asymmetry of adult baboons (Marie et al., 2018). However, because of the immature brains of the newborn subjects, T2w MRI signal was used instead of T1w MRI signal for manual delineation for the first longitudinal scans.
In fact, the T2w MRI signal is sensitive to the free water present in voxels. The proliferation of membranes due to synaptogenesis and the process of myelination will decrease the proportion of free water in the gray matter voxels and thus darken the images during maturation of the first human year post-natal. Therefore, a higher contrast is generated in comparison to T1w images in early immature brains, which helps for better delimitation (Dehaene-Lambertz and Spekkel, 2015).

Following the procedures used in humans (Jansen et al., 1989), great apes (Hopkins et al., 1998; Hopkins and Nir, 2010; Cantalupo et al., 2003) and Old-World monkeys (Marie et al., 2011), the surface of the PT homolog was measured in the coronal plane. The T2w images of every subject were imported in ITK-Snap. In these, the region of interest was manually traced in the coronal plan on the individual native space with the ITK-Snap tool “Paint-Brush Mode” with feature round brush size 1, using a touch-pad-driven pointer (Wacom Cintiq® 13HD).

Coronal planes were used because they display the full depth of the sylvian fissure, of which the Planum Temporale is its floor. As described by Marie et al., 2018, delineation of the PT was performed as follows:

The posterior border of the PT was characterized by the last caudal slice displaying the Sylvian fissure. The anterior border was defined by the full closure of the Insula sulcus and grey matter. This technique was chosen due to the inconsistency of the presence of the Herchis’s gyrus (see Marie et al., 2018; Lyn et al., 2011 for discussions).

For each slice, the delineation was traced on the most ventral boundary between the sulcus and the grey matter. In order to balance the rater’s possible handedness bias, tracing for each subject was randomly undertaken either from the most medial to the most lateral pixel of the Sylvian fissure or from the most lateral to the most medial pixel. This step was repeated on the next slice, moving posteriorly until the Sylvian fissure fell out of view.

Next, a surface area was generated across all slices for each hemisphere independently in a given subject (see Fig. 1A). For each subject, an Asymmetry Quotient (AQ) of the left (L) and the right (R) surface areas was computed AQ = (R − L) / [(R + L) x 0.5] with the sign indicating the direction of asymmetry (negative: left side, positive: right side) and the value, the strength of asymmetry. Further, as reported by Hopkins and Nir (2010) for humans and great apes, the AQ was also used to classify the subjects as left-hemispheric biased (AQ ≤ 0.025), right biased (AQ > 0.025), or nonbiased (0.025 < AQ < 0.025). A threshold of 0.025 represents a 2.5% difference in surface area between left and right PT.

A second rater, blind to the side, confirmed the measures of the PT in a subsample of 15 individuals for both hemispheres (inter-rater correlation coefficient for 30 PT tracing was r(30) = 0.94, p < 0.0001). 2.5. Statistics


3.1. PT structural asymmetry

We found a significant leftward asymmetry of the PT surface at a group-level in 35 newborn baboons (t0) according to a one sample t-test in the 35 subjects’ AQ scores (see Fig. 1B), Mean AQ = −0.058 ± 0.067 SD; t(34) = 5.15, p < 0.0001. Categorization of individual AQ showed also a majority of leftward PT-biased individuals (see Fig. 1C). 25 baboons exhibited a leftward hemispheric PT bias (71.4%) whereas 2 exhibited a rightward PT bias (5.7%) and 8 no PT bias (22.9%), a distribution quasi-identical than the one found in human infants (Wada, 1975). We found no difference of distribution between infant baboons and infant humans according to chi-square (p = 0.25 for three groups “Left bias, Right bias, no bias” and p = 0.20 for two groups “Left bias, Right bias”). The number of leftward PT-biased baboons was significantly greater than the number of rightward PT-biased subjects according to chi-square test (χ2 = 19.59, p < 0.0001).

3.2. Age classes’ comparison of PT lateralization’s strength

Follow-up analysis among the 29 rescanned baboons when reaching 7 to 10 months of age (t1) showed a significant increased strength of PT asymmetry (Mean Absolute AQ score, M = 0.105 ± 0.065 SD) in comparison to their earliest age class according to a paired sample t-test (Mean Absolute AQ score, M = 0.073 ± 0.049 SD), t(28) = 2.39, p = 0.024 (see Fig. 1D) as well as a significant correlation between the two MRI sessions, r(29) = 0.55, p < 0.002.

3.3. Left, right PT surface areas

At t0, the mean PT surface areas were in the left hemisphere: M = 50.34 mm² ± 9.27 SD (in males M = 51.07 mm² ± 9.80 SD; in females M = 49.24 mm² ± 9.17 SD) and in the right hemisphere: M = 47.44 mm² ± 8.93 SD (in males M = 48.53 mm² ± 9.35 SD; in females M = 45.79 mm² ± 7.78 SD).

At t1, the mean PT surface areas were in the left hemisphere: M = 58.48 mm² ± 8.0 SD (in males M = 59.23 mm² ± 8.07 SD; in females M = 57.67 mm² ± 7.75 SD) and in the right hemisphere: M = 55.73 mm² ± 8.65 SD (in males M = 57.07 mm² ± 9.99 SD; in females M = 54.28 mm² ± 6.64 SD).

3.4. Age, sex, brain size effect

Multiple linear regression analyses showed that the right PT surface (p = 0.001), the left PT surface (p = 0.02) and age (p = 0.033) predict PT asymmetry strength but not the subjects’ side. As we performed a leftward PT asymmetry (M = 0.105 ± 0.065 SD) in comparison to their earliest age class according to a paired sample t-test (Mean Absolute AQ score, M = 0.073 ± 0.049 SD), t(28) = 2.39, p = 0.024 (see Fig. 1D) as well as a significant correlation between the two MRI sessions, r(29) = 0.55, p < 0.002.

4. Discussion

Our results showed that early post-natal nonhuman primate infants present a significant human-like neuroanatomical asymmetry of the Planum Temporale surface (PT) in favor of the left hemisphere. This finding is clearly consistent with early PT asymmetry found in human newborns and infants (Chi et al., 1977; Dubois et al., 2010; Gäsler et al., 2011; Hill et al., 2010; Wada, 1975; Wiltson and Pallie, 1973) although measurement methods, Left-Right-Ambi classification threshold and statistical power in terms of sample size differ as well as age class equivalence which overall make interspecies comparison challenging. Nevertheless, the distribution is quasi-identical to the ones reported in both human infants and human adults (Geschwind and Levitky, 1968) but also in adult chimpanzees (Hopkins and Nir, 2010) and adult baboons (Marie et al., 2018). Our findings are also somewhat consistent with averaged-brain leftward asymmetries found in infant Rhesus macaques within large temporal clusters which seem to overlap with PT according to an automated source-based method (Xia et al., 2019). Such a similar age-related phenomenon was also described in human infants by Wada (1975). Interestingly, we found that the direction of individual PT asymmetry is consistent across age classes while its strength is increasing with age. In contrast, no sex or brain size effects were found on direction or strength of PT asymmetry. This finding is not consistent with the idea that increase in PT asymmetry in Hominidae evolution was due to increase in brain volume (Pilcher et al. 2001). Additionally, if strength of PT asymmetry is affected by sex in human adults (Hirstein et al., 2019), it seems not the case in adult baboons (Marie et al., 2018), infant baboons and human infants (Dubois et al. 2010).

This finding in a non-linguistic species clearly questions the historical idea that such a maturational effect of the PT asymmetry’s strength
is related to language development in human infants (Wada, 1975). One could ask whether the existence of the asymmetry shortly after birth has an innate, and thus, genetic component as hypothesized for human infants (Hill et al., 2010) or to what extent it is rather influenced by pre- and post-natal experience. In any case, the collective findings clearly provide additional support for the phylogenetic continuity between human and nonhuman primate species about such a brain asymmetric feature. Such a continuity extended to the earliest postnatal stage of development across both species may question the early PT asymmetry as a human newborn-specific marker of the language-ready brain.

Structural lateralization of such a language area may not solely account for a pre-wired brain for language acquisition as it was supposed for human babies (Dehaene-Lambertz et al., 2002).

However, it remains unclear which factor is driving such a common early asymmetric feature of the brain anatomy among human and nonhuman infants. One potential explanation is that early PT structural asymmetry might have nothing to do with development of language lateralization, given some studies in adults reported no match between structural and functional asymmetry of this region (Keller, 2011; Greve, 2013).

Nevertheless, the most recent study addressing this question in adults contradicts such a hypothesis (Tzourio-Mazoyer et al., 2018). Although the lack of match was confirmed between structural and functional asymmetry of the PT in a language task, structural PT asymmetry was found associated with functional lateralization of an adjacent auditory area at the end of the Sylvian fissure, suggesting its links with language lateralization.

Therefore, another potential explanation is that the early PT structural asymmetry in both human and nonhuman infants might predict the development of homolog communicative functions, which still form a foundation for core aspects of the human language system. Determining such common developing functions between species remains highly speculative, given the lack of longitudinal studies in infants on the emergence of brain-behavior relationships. Nevertheless, based on neuroimaging studies in nonhuman primate focusing on adults, it might be not excluded that shared properties of communicative systems in human and nonhuman primates could be related to PT structural asymmetry. For instance, previous studies in monkeys and apes have reported human-like functional lateralization for processing conspecific calls. However, its overlap with PT anatomical region remains unclear as well as the direction of the functional lateralization (i.e., toward left...
versus right hemisphere) which are inconsistent across the liter-ature (e.g. Poremba et al.; 2004; Gil-da-Costa and Hauser 2006; Petkov et al. 2008; Joly et al., 2012). Alternatively, some authors have proposed that properties of the communicative gestural system in non-human primates could constitute another potential functional candidate of PT specialization. In fact, whereas production of communicative manual gestures have been found highly lateralized in favor of the right-hand in both baboons and chimpanzees (Meguerditchian et al., 2013), a contralateral relation between PT structural asymmetry and hand preferences for communicative gesture was reported in adult chimpanzees (Hopkins and Nir, 2016; Meguerditchian et al., 2012). These latter findings have thus suggested that shared property between gesture signaling in apes and language system in humans might be both ultimately related to this asymmetry feature of the temporal lobe anatomy (Meguerditchian et al., 2012). Whether similar gestural functional special-ization of the structural PT asymmetry exists in baboons has been not investigated yet although both chimpanzees and baboons have shown similar leftward structural asymmetry of the PT as well as similar right-ward patterns of gestural communication's manual lateralization.

Further studies in our sample of infant baboons would help us de-terminate the potential relationship between these early PT structural asymmetry and development of manual lateralization of communicative gestures.

In conclusion, the present finding in nonhuman infants provides additional support to the hypothesis of a continuity between nonhu-man and human primates concerning leftward structural PT asymmetry. Sharing such an anatomical feature of the brain at this earlier postna-tal stage of development reinforced thus the idea of its common origins from our distant evolutionary ancestor, dated back 25–35 million years ago, although its potential link with the language-brain remains an open question.

Declaration of Competing Interest

Authors declare no competing interests.

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Author contributions

Y.B and A.M prepared the paper and the revision. Y.B. performed the tracing and analyses. C.B. performed the interrater tracing. J.S. parametrized the MRI sequences and optimized the MRI acquisition setup. B.N. designed the baboons' monitoring programs. L.V., L.R., R.L. and L.G. designed the specific procedures of welfare, anesthesia, mon-itoring and preparation of baboons in the MRI machine. J.LA supervised and coordinated the MRI session. A.M. designed and supervised the study and MRI acquisitions.

Data and materials availability

All data is available in the supplementary materials.

Data availability statement

Our data will be available online upon publication and is attached to this submission in the supplementary material.

Supplementary materials

Supplementary material associated with this article can be found in the online version, at doi:10.1016/j.neuroimage.2020.117575.

References


4. Chapter: Planum Temporale grey matter volume asymmetries in newborn monkeys (*Papio anubis*)

Published article:

Planum temporale grey matter volume asymmetries in newborn monkeys (*Papio anubis*)

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Abstract
The Planum temporale (PT) is one of the key hubs of the language network in the human brain. The gross asymmetry of this perisylvian region toward the left brain was considered as the most emblematic marker of hemispheric specialization of language processes in the brain. Interestingly, this neuroanatomical signature was documented also in newborn infants and preterms, suggesting the early brain’s readiness for language acquisition. Nevertheless, this latter interpretation was questioned by a recent report in non-human primates of a potential similar signature in newborn baboons *Papio anubis* based on PT surface measures. Whether this “tip of the iceberg” PT asymmetry is actually reflecting asymmetry of its underlying grey matter volume remains unclear but critical to investigate potential continuities of cortical specialization with human infants. Here we report a population-level leftward asymmetry of the PT grey matter volume in vivo 34 newborn baboons *P. anubis*, which showed intra-individual positive correlation with PT surface’s asymmetry measures but also a more pronounced degree of leftward asymmetry at the population level. This finding demonstrates that PT leftward structural asymmetry in this Old World monkey species is a robust phenomenon in early primate development, which clearly speaks for a continuity with early human brain specialization. Results also strengthen the hypothesis that early PT asymmetry might be not a human-specific marker for the pre-wired language-ready brain in infants.

Keywords Hemispheric specialization · Lateralization · Nonhuman primates · Language evolution

Introduction
The majority of language processes is asymmetric in the human brain, involving a specialization of the left hemisphere (Vigneau et al. 2006). The most emblematic marker of such a language cerebral organization is the gross asymmetry of the Planum temporale (PT) toward the left hemisphere. This perisylvian region, which constitutes the floor of the sylvian fissure, posterior to Heschl’s gyrus and overlaps with Wernicke’s area, is one of the key hubs of the language network in the human brain. In fact, the left PT was significantly activated in a variety of language processing tasks in adults (Shapleske et al. 1999; Vigneau et al. 2006; Josse et al. 2006).

Since the first discovery that the PT was larger in the left hemisphere than the right in most adults (Geschwind and Levitsky 1968), it remains unclear, whether this feature constitutes a good marker of language functional lateralization. While some studies reported no match between structural and functional asymmetry of this region (Keller et al. 2011; Greve et al. 2013), clinical studies found that atypical PT structural asymmetry were associated with multiple language deficits (Borovsky et al. 2007; Dronkers et al. 2004; Foundas et al. 2004; Wernicke 1874). In addition, in a recent study, higher density of dendrites and axons in the PT were associated with faster neurophysiological processing of auditory speech (Ocklenburg et al. 2018). Moreover, in a second recent study, structural PT asymmetry was found associated with functional lateralization of an adjacent auditory area at the end of the sylvian fissure during a language task (Tzourio-Mazoyer et al. 2018).

Interestingly, leftward PT asymmetry was detected early in the development at both the functional level in
3 month-old infants in response to speech (Dehaene–Lambertz et al. 2002) and at the structural level in newborn and preterms (Witelson and Pallie 1973; Wada 1975; Chi et al. 1977; Dubois et al. 2010; Hill et al. 2010; Glasel et al. 2011). Such early features of language brain laterality suggest that the infant brain might be already prewired for language acquisition (e.g. Dehaene–Lambertz et al. 2002).

However, the human uniqueness of structural PT asymmetry was questioned by studies highlighting also a population-level leftward asymmetry by PT surface measures in chimpanzees (Gannon et al. 1998; Hopkins et al. 1998; Spocter et al. 2020) and in baboons (Marie et al. 2018). In this latter Old World monkey species, PT leftward surface biases were found not only in adults but also recently in newborn baboons [Becker et al. 2021, see also Xia et al. (2019) for a study in macaques using cortical surface-based morphometry], suggesting it might reflect the asymmetry of its underlying grey matter volume and is thus not specific to human early brain development. In fact, PT surface area measures quantified the depth of the sylvian fissure’s floor. It might be thus not excluded that the asymmetry of the sulcal surface area of this region might be an appropriate indicator of the asymmetry of the juxtaposing grey matter volume of the PT. This hypothesis is supported by few studies in adult chimpanzees which focussed on PT grey matter volume asymmetry according to both ROI manual tracing (Hopkins and Nir 2010; Lyn et al. 2011) and voxel-based morphometry (Hopkins et al. 2008), all showing consistent leftward asymmetry with PT surface measures.

In the present study, we further explore this hypothesis in 34 newborn baboons by quantifying the grey matter volume of the left and right PT from in vivo MRI brain scans (Becker et al. 2021). The aim of the follow-up study is thus to investigate early individual and population-level asymmetries of the PT grey matter volume in newborn non-human primates and their potential consistencies with PT surface asymmetries measures within the same cohort of subjects used in Becker et al.’s study (2021).

### Materials and methods

#### Subjects

Subjects ranged from 4 to 165 days of age (Mean 32.63, SD 6.13) and included 21 males and 14 females. (see Table in Supplementary methods with subjects’ details). All monkeys are housed in social groups at the Station de Primatologie CNRS (UPS 846, Rousset, France) and have free access to outdoor areas connected to indoor areas. All subjects are born in captivity from 1 (F1) to 2 generations (F2). Wooden and metallic structures enrich the enclosures. Feeding times are held four times a day with seeds, monkey pellets and fresh fruits and vegetables. Water is available ad libitum.

#### MRI image acquisition

Structural magnetic resonance images (MRI) were collected from a sample of 35 baboons (September 2017–March 2020). Animals were minimally anesthetized by a veterinarian; and vital functions were monitored during the scans. High-resolution structural T1 weighted brain images were obtained with MPRAGE sequences (0.4 mm isotropic, TR = 2500 ms, TE = 3.01 ms) with the subject in the supine position on a Siemens 3T Magnetom prisma scanner and using two 11 cm receive-only loop coils [for more detailed procedure: Becker et al. (2021)]. At the end of the MRI session, when fully awakened from anesthesia, baboons were carefully put back with their mother and then transported for immediate (or delayed) reintroduction into their social groups under staff monitoring.

#### Preprocessing of anatomical MRI

Anatomical T1w images were noise corrected with the spatially adaptive nonlocal means denoising filter (Manjón et al. 2010) implemented in Cat12 toolbox (http://www.neuro.

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Fig. 1 a 3D reconstruction of a newborn baboon brain with the PT region highlighted by the white lines b Coronal slice of the same subject with the delineation of the sylvian fissure’s floor (in red), used for PT surface measures c Coronal slice of the same subject with the delineation of the grey matter (in red) underneath the sylvian fissure, used for PT volume measures
uni-jena.de/cat/) included in SPM12 (http://www.fil.ion.ucl.ac.uk/), which runs on MATLAB (R2014a). Next, each image was manually oriented using ITK-Snap 3.6 according anterior and posterior commissures plane and the interhemispheric fissure plane.

**Manual delineation of the planum temporale’s grey matter volume**

Manual delineation was conducted with “ANALYZE 11.0 (AnalyzeDirect)” software and following the delimitation instructions established in previous PT studies in non-human primates using MRI (e.g., Hopkins and Nir 2010; Lyn et al. 2011; Meguerditchian et al. 2012; Marie et al. 2018; Becker et al. 2021). The delineation of the posterior edge of the PT is defined by the most caudal section showing the Sylvian fissure (see Fig. 1). In humans, the anterior edge of the PT is delimited by Heschl’s gyrus, however, in baboons Heschl’s gyrus is not clearly detectable, therefore to delineate the anterior edge of the PT here, the most anterior cut including the Sylvian fissure was used when the insula closes completely (when the insula fissure disappears completely posteriorly). For each slice, manual tracing was conducted from the medial most point of the Sylvian fissure, to the most lateral point, following the most ventral edge of the fissure. Next, the raters followed the grey matter to its most inferior edge of the grey/white matter boundary. When ambiguous, the imaginary prolongation of the Sylvian fissure was used to differentiate between the grey matter of interest and the more dorsal gyrus. This step is repeated on the next cut, advancing posteriorly, until the Sylvian fissure disappears. If the fissure forked in an ascending or descending direction, it was preferable to follow the descending one. This manual tracing was done on the coronal plane and not sagittal, as it gives the best assessment of the total depth of the Sylvian pit, which is the “ground” of the PT. The manual delimitation was carried out via a graphic tablet (WACOM cintiq 13HD). Out of the 256 slices included in the MRI images, the PT appeared in about 20 slices (Supplementary Fig. 1).

For each subject, an asymmetry quotient (AQ) of the left (L) and the right (R) grey matter volume was computed AQ = (R − L)/(R + L) × 0.5 with the sign indicating the direction of asymmetry (negative: left side, positive: right side) and the value, the strength of asymmetry. Further, as reported by Hopkins and Nir (2010) for humans and great apes, the AQ was also used to classify the subjects as left-hemispheric biased (AQ ≤ − 0.025), right biased (AQ ≥ 0.025), or non-significantly biased “ambi” (− 0.025 < AQ < 0.025).

To reduce potential observer-dependent manual tracing biases, all the PTs grey matter volume were traced by a rater different from the one who traced the PT surface in Becker et al. (2021). The rater of the present study was blind to the PT surface’s tracing, data and results of Becker et al. (2021). Statistics were conducted with R 3.6.1 (R Core Team, 2017, https://www.R-project.org/).

**Results**

**PT grey matter volume measures**

We found a significant leftward asymmetry of the PT grey matter volume at a group-level in 34 newborn baboons according to a one sample t test in the 34 subjects’ AQ scores (see Fig. 2), Mean AQ = − 0.121, ± 0.169 SD; t(33) = − 4.2, p < 0.0001. Categorization of individual AQ showed also a majority of leftward PT-biased individuals: 24 baboons exhibited a leftward hemispheric PT bias (70.6%) whereas 7 exhibited a rightward PT bias (19.6%) and 3 no PT bias (8.8%). The number of leftward PT-biased individuals was significantly greater than the number of rightward PT-biased according to chi square test ($\chi^2 = 21.94$, $p < 0.0001$).

Multiple linear regression analyses showed that the right PT volume ($p < 0.001$) and the left PT volume ($p < 0.001$) predict PT asymmetry strength, but not the subject’s sex, age nor brain volume (see Fig. 3).

![Fig. 2](image-url)
Correspondence between PT surface and PT grey matter measures

Within the 34 individuals for whom data of PT surface and PT grey matter volume measures were independently traced by two different raters blind to the results of each other, a significant positive intra-individual correlation of AQ scores was found between PT surface and PT grey matter volume. $r(34)=0.36$, $p<0.037$.

In comparison to previous surface PT measures (Becker et al. 2021), 22 were consistent in hemispheric lateralization classification (i.e., 20 leftward, 1 rightward and 1 ambi) and 4 subjects switched direction of hemispheric PT bias (i.e., from leftward bias for PT surface to rightward bias for PT grey matter volume). Among the remaining 8 subjects, 6 which previously showed no significant bias (i.e., “ambi”) for the PT surface were found significantly lateralized for the PT grey matter volume and 2 which were previously classified as significantly lateralized for the PT surface were classified as “ambi” for the PT grey matter volume.

Discussion

We find for the first time both individual and leftward population-level grey matter volume asymmetries of the Planum temporale not only in Old World monkeys but also in a newborn non-human primate. These results showed intra-individual positive correlation with previous published PT surface measures on the same subjects as well as consistent leftward PT asymmetry (Becker et al. 2021) and suggesting PT surface measures may therefore reflect its underlying grey matter volume.

Interestingly, we found that the direction of individual PT surface and volume asymmetry is not affected by age within this early age class. However, in a previous longitudinal paper (Becker et al. 2021), we found that the degree of PT surface asymmetry was increasing latter in the development (i.e., at the upper age class: 7–10 month of age), suggesting that the strength of the PT GM volume asymmetry should also increase at this upper age class. In addition, no sex or brain size effects were found on direction or strength of PT surface and GM volume asymmetry. This finding contrasts findings in adult baboons (Marie et al. 2018) and the hypothesis of PT asymmetry increase due to increase of brain volume in Hominidae evolution (Pilcher et al. 2001). In addition, an absent sex effect in infant baboons, adult baboons (Marie et al. 2018) and human infants (Dubois et al. 2010) contrasts findings in human adults (Hirnstein et al. 2019).

The distributions of individual PT hemispheric preferences (left, right or ambi) are quite similar between volumetric grey matter and surface measures, especially for the left lateralized subjects, although some inconsistency was noticed at the individual-level in a minority of subjects. It remains unclear whether those variations are due to inter-rater-dependent variability in the measures, which leads few subjects to switch categories or to the possibility that PT surface measures are not entirely perfect “tip of the iceberg” predictors of the PT grey matter volume, especially for the subjects initially classified as ambiguously biased for PT surface. In fact, almost all of those latter “ambi” newborns (six out of seven) were found to be significantly lateralized for PT grey volume. In addition, AQ values were overall higher in grey matter measures (AQ $-0.121$ 12.1%) compared to surface measures (AQ $-0.073$ 7.3%). A similar effect was found in Hopkins and Nir’s paper (2010), which showed a 4.96% larger left hemisphere when measuring its surface and 6.63% larger hemisphere when measuring its grey matter. Therefore, measures of grey matter volume may be more likely to capture interindividual differences of the PT asymmetry, whereas the surface measures may only scratch the top of the PT iceberg. Whereas the surface area and the cortical thickness are the two components of the cortical volume, a recent study of brain structural asymmetry in 17,141 humans showed that “regarding surface area, population-level asymmetry was generally more prominent compared with that of cortical thickness” (Kong et al. 2018). Whether surface asymmetry is the best predictor of volume asymmetry over cortical thickness remains still unclear in humans although the leftward asymmetry of surface area in regions found in this study such as the supramarginal gyrus is consistent with the widely observed volume asymmetry in the perisylvian regions (Kong et al. 2018).

Interestingly, in a previous study in chimpanzees, Hopkins and Nir (2010) noted that leftward PT grey matter volume asymmetry constituted a better marker for the chimpanzee’s right-hand preference in communicative pointing gestures than PT surface (but see Meguerditchian et al. 2012). This latter study suggested the hypothesis that asymmetry of
PT grey matter volume might be associated to functional asymmetry related to properties of gestural communication in apes, which have been found to share common features with human language such as intentionality, flexibility or referential properties (i.e., Liebal et al. 2013). Communicative manual gestures in baboons were also described in the literature (e.g., Molesti et al. 2020) and elicited, just like in the chimpanzees, an increased use of the right-hand in comparison to manipulative actions (Meguerditchian et al. 2013). Follow-up behavioural observations on gestural lateralization for communication in our sample of growing baboons will advance this question, once the focal subjects develop their full gestural repertoire. Specifically, taking advantage of the stronger PT asymmetries described in the present study for grey matter volume in comparison to surface measures, we could further investigate whether those early brain asymmetries might predict the gestural lateralization’s emergence in later development.

In conclusion, the present finding in non-human infants provides additional support to the hypothesis of a continuity between nonhuman and human primates concerning early leftward structural PT asymmetry in brain development. Early PT asymmetry might be thus not a human-specific marker for the pre-wired language-ready brain in infants. Nevertheless, it might not be excluded that this common anatomical signature is related to an ancient shared cognitive process at the heart of language evolution.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00429-021-02278-9.

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Authors’ contributions YB and AM prepared the paper and the revision. RP performed the tracing and analyses. JS parametrized the MRI sequences and optimized the MRI acquisition setup. LV and LR designed and performed respectively the specific procedures of welfare, anesthesia, monitoring and preparation of baboons in the MRI machine. AM designed and supervised the study and MRI acquisitions.

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Declarations

Ethical approval All animal procedures were approved by the “C2EA-71 Ethical Committee of neurosciences” (INT Marseille) under the number APAFIS#13553-20180215154779 v4 and has been conducted at the Station de Primatologie under the number agreement C130877 for conducting experiments on vertebrate animals (Roussel-Sur-Arc, France). All methods were performed in accordance with the relevant French law, CNRS guidelines and the European Union regulations (Directive 2010/63/EU).

Data and materials availability See Supplementary material.

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5. Chapter: Planum Temporale asymmetry in newborn monkeys paves the way for gestural communication development

Submitted article:
Planum Temporale asymmetry in newborn monkeys paves the way for gestural communication development

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The Planum Temporale (PT) is a key language area and is structurally and functionally left-lateralized in pre-linguistic infants. Therefore, the PT was considered a marker of the uniquely human pre-wired brain for language acquisition.

However, recent studies have now reported a similar structural asymmetry in newborn baboons. Its functional correlate, which underlays language processing and which is shared with these non-linguistic monkeys remains unknown. Here we demonstrate that direction of PT grey matter asymmetry in newborn baboons predicts the development of later manual lateralization for communicative gesture. In other words, newborns with a larger left-than-right PT developed more likely a right-handed communication once juvenile. No link was found with handedness for non-communicative actions. This finding contrasts the idea that the PT asymmetry constitutes a human-specific marker for language development. The PT asymmetry might rather be a pre-wired neural underpinning of intentional communication, shared between Old World monkeys and humans.

Introduction:
Language is a prominent feature of the human species (e.g., Boe et al., 2019). Nonhuman primates, however, share some "domain general" cognitive properties that are essential for language processes (e.g., Becker & Meguerditchian, 2021). Whether these shared cognitive properties of humans and nonhuman primates are the result of continuous or convergent evolution can be examined by comparing their respective underlying structure: the brain.

A key structure for language in the brain is the Planum Temporale (PT), a part of Wernicke's area (Hickok & Saberi, 2012). Indeed, the PT has been found to be structurally larger in the
Functionally, it has also been shown to be activated in a variety of language processing tasks (e.g., Becker & Meguerditchian, 2021). Interestingly, PT left asymmetry has also been found very early in infant development, both at the structural (e.g., Dubois et al., 2010) and functional level (Dehaene-Lambertz et al., 2002). Such early features of language brain lateralization suggest that the infant brain may already be prewired for language acquisition (e.g., Dehaene-Lambertz et al., 2002).

However, the uniqueness of structural PT asymmetry in adult humans has been questioned by studies in adult chimpanzees and baboons, which showed similar left asymmetry (e.g., Spocter et al., 2020). Regarding early developmental onset, we recently reported the existence of the PT asymmetry in newborn baboons (Becker et al., 2021a, b). This suggests a shared signature of a common ancient cognitive process at the heart of language evolution (Becker et al., 2021a). However, it is unclear for which cognitive process or behavior the PT asymmetry evolved. One hypothesis comes from research in chimpanzees in which PT asymmetry has been demonstrated in the context of communicative gestures (Meguerditchian et al., 2012). In that study, the direction of hand preference (left or right) for communicative gestures explained the variability in PT asymmetry between subjects (Meguerditchian et al., 2012). Nonetheless, it is unknown whether a similar relationship exists in Old world monkeys. It is also unknown whether the behavioral experience modulates its underlying brain structure, or inversely, whether the early brain structure determines future behavioral development.

Therefore, in this study, we related gray matter PT measurements from newborn baboons (data from Becker et al. 2021b) (~2 weeks old) to the manual behavior of the same subjects once they reached their behavioral repertoire (~2 years old).

**Results:**

Subjects were divided into two groups, due to their direction of PT asymmetry (19 left, 8 right) (See Becker et al., 2021b). As the a priori prediction concerned a contralateral effect, one tail comparisons where conducted. One sample t-test highlighted a significant positive handedness for communication for the left biased PT group ($p < .006$), which was not found for the right-biased group ($p > .3$) (Figure 1). Two-sided t test demonstrated a significant difference between groups ($p < .042$). Further, a logistic regression was performed to investigate the effects of the asymmetry quotient of the Planum Temporale at birth on the likelihood of becoming left or right-handed in communicative gesture. As the a priori prediction concerned a contralateral effect, one tail comparisons where conducted. The predictor variable AQ was found to
contribute to the model. The unstandardized Beta weight for the Constant; $B = (.811)$, $SE = .425$, $Wald = 3.642$, $p < .028$. The unstandardized Beta weight for the predictor variable; $B = (-5.453)$, $SE = 3.251$, $Wald = 2.814$, $p < .046$ (Figure 2).

Figure 1. Distribution of Handedness Index (HI) for gestural communication at juvenile age for subjects that were classified left biased (red) and right biased (blue) for the Planum Temporale (PT) at birth. HI values inferior to zero indicate leftward lateralization, HI values superior to zero indicate rightward lateralization. Note the significant rightward handedness lateralization for left biased PT ($p < .05$) and the significant difference between the two groups ($p < .05$).
Figure 2. Significant logistic regression model ($p < .05$) of the outcome probability of having a discrete category “left- or right handers in communicative gesture” by the asymmetry quotient of the Planum Temporale at birth.

**Methods:**

In fact, baboons and great apes can be classified as left or right-handed - for non-communicative manipulative actions or for their manual preferences in communicative actions (Molesti et al., 2019; Meguerditchian et al., 2013). While the independence of these measures is unclear, it was shown that the proportion of right handers increase in the communicative gesture classification even if these individuals have been classified as left handers in the non-communicative action task (Meguerditchian et al., 2013). Handedness for manipulative actions was assessed using the well-documented bimanual coordinated “Tube task” (Meguerditchian et al., 2013). Hand use was recorded when extracting food with a finger out of a PVC tube, hold by the other hand. Communicative gesture was defined as a movement of the hand directed
to a specific partner or audience in order to affect its behaviour (Molesti et al., 2019). The “Hand slapping” gesture was previously found optimal for measuring such gestural communication’s lateralization in the baboon (Meguerditchian et al., 2013). It consists of a frequent threatening gesture by slapping or rubbing repetitively the hand on the ground in order to intimidate an out of reach recipient. For each subject and both behaviors, a handedness index of the left (L) and the right (R) hand was computed $HI = (R - L) / (R + L)$ with the sign indicating the direction of asymmetry (negative: left side, positive: right side) and the value, the strength of asymmetry.

The 26 healthy infant baboons (Papio anubis; 10 females, 16 males, 4 to 165 days of age) for which both grey matter measurements and behaviour data was available, lived in social groups at the Station de Primatologie (CNRS) with free outdoor access and without any food or water restriction. For obtaining MRI images animals were anesthetized by a veterinarian; and vital functions were monitored during the scans. T1 MPRAGE images (0.4 mm isotropic, TR = 2500ms, TE = 3.01ms) were acquired on a Siemens 3T Magnetom Prisma scanner using two 11cm receive-only loop coils (see Becker et al. 2021a for more details).

While historically the PT constitutes a surface, we have hypothesized that the grey matter underneath this key area will be a better predictor for behavior than its surface, which would constitute the “tip of the iceberg” (Becker et al., 2021b, see also Hopkins & Nir, 2010).

The PT grey matter was measured manually by a blind tracer and correlated with surface measurements (Becker et al., 2021b). Tracing was conducted on ANALYZE 11.0 (AnalyzeDirect) software and following the delimitation instructions established in previous PT studies in nonhuman primates using MRI (e.g., Hopkins and Nir, 2010; Becker et al., 2021a). Its anterior border consists of the last coronal slice of insular grey matter and its posterior border when the Sylvian fissure falls out of view. Further, as reported by Hopkins and Nir (2010) for humans and great apes, an asymmetry quotient (AQ) was computed of the left (L) and the right (R) gray matter volume: $AQ = (R - L) / [(R + L) \times 0.5]$. The AQ was used to classify the subjects as left-hemispheric biased ($AQ \leq -0.025$), right biased ($AQ \geq 0.025$), or non-significantly biased “ambi” ($-0.025 < AQ < 0.025$).

**Discussion:**

Our results show that an early PT asymmetry predicts future handedness development for communicative gesture but not future handedness development for non-communicative
actions. We therefore propose the gestural communication system as a potential candidate for an evolutionary shared cognitive process, which is at the heart of communication across primates. Indeed, this result demonstrate an evolutionary continuity between baboons, chimpanzee and humans, as in all three species a link between communication and cerebral asymmetry was found (Meguerditchian et al., 2012; Dehaene-Lambertz et al., 2002). In addition, we highlight a direction of causality between communicative behavior and underlying brain structures. Indeed, the PT asymmetry is already present soon after birth and may shape the much later developing hand preference for gestural communication. Our results also indicate that the PT may not have solely evolved as a computational hub for complex sounds (Griffiths & Warren, 2002), but also seems to be specialized for communicative production. In fact, an alternative view is that the PT may be composed of functional subfields, with one of them performing motor processes (Hickok & Saberi, 2012). Indeed, recent results in implanted human patients showed that stimulation of the PT selectively disrupts speech production (Forseth et al., 2020). Our results are in agreement with results in adult baboons concerning Broca’s homolog (Becker et al., 2021c) and highlight a conserved gestural mechanisms across Old world monkeys and humans that is in the heart of language evolution.

References:


6. Chapter: Broca’s cerebral asymmetry reflects gestural communication’s lateralisation in monkeys (Papio anubis)

Published article:
Broca's cerebral asymmetry reflects gestural communication's lateralisation in monkeys (*Papio anubis*)

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Abstract

Manual gestures and speech recruit a common neural network, involving Broca’s area in the left hemisphere. Such speech-gesture integration gave rise to theories on the critical role of manual gesturing in the origin of language. Within this evolutionary framework, research on gestural communication in our closer primate relatives has received renewed attention for investigating its potential language-like features. Here, using in vivo anatomical MRI in 50 baboons, we found that communicative gesturing is related to Broca homologue’s marker in monkeys, namely the ventral portion of the Inferior Arcuate sulcus (*IA sulcus*). In fact, both direction and degree of gestural communication’s handedness – but not handedness for object manipulation are associated and correlated with contralateral depth asymmetry at this exact *IA sulcus* portion. In other words, baboons that prefer to communicate with their right hand have a deeper left-than-right *IA sulcus*, than those preferring to communicate with their left hand and vice versa. Interestingly, in contrast to handedness for object manipulation, gestural communication’s lateralisation is not associated to the Central sulcus depth asymmetry, suggesting a double dissociation of handedness’ types between manipulative action and gestural communication. It is thus not excluded that this specific gestural lateralisation signature within the baboons’ frontal cortex might reflect a phylogenetical continuity with language-related Broca lateralisation in humans.

Editor’s evaluation

This is an elegant, well-designed study, filling a gap regarding structural asymmetries in Broca’s area for Old World monkeys. Using a good number of subjects (50 baboons), the authors build on earlier behavioral work pointing to handedness contrasts between communicative vs manipulative gestures, and tested whether the lateralisation effect associated specifically with communicative gestures manifested itself in the depth asymmetry of the ventral Inferior Arcuate (*IA*) sulcus [Broca’s area homologue], but not in the central sulcus. The results of the experiments indeed show a dissociation between communicative vs manipulative gestures, with only the communicative gestures being associated with an *IA* sulcus depth asymmetry tracking lateralized hand use. The authors point to a captivating phylogenetic continuity between language lateralisation in humans and brain asymmetries related to gestures in nonhuman primates.
Introduction

Broca’s area and its left hemispheric specialisation has historically been considered as the centre of speech production. Even if such a modular conception of language’s neural bases was questioned by models of plastic and large distributed networks (Friederici, 2017; Hickok and Poepppel, 2007), it is still well acknowledged that Broca’s area remains a key node for language specialisation within this neural distributed network. Complementary work thereby highlighted Broca’s area as an interface between speech and multimodal motor integration including gesture and mouth movements (Gentilucci and Dalla Volta, 2008). Broca’s area is also known for its involvement in motor planning, sequential, and hierarchical organization of behaviours, such as linguistic grammar or tool use and tool making (Gentilucci and Dalla Volta, 2008; Koechlin and Joubert, 2006; Stout et al., 2015; Corballis, 2015; Wakita, 2014). This body of work raises evolutionary questions about the role of the motor system and gestural communication in language origins and its brain specialisation. Therefore, a growing number of researchers proposed that language organisation took some of its phylogenetical roots into a gestural system across primate evolution (Gentilucci and Dalla Volta, 2008; Corballis, 2015; Tomasello, 2008). Consequently, whereas comparative language research has focused on the potential continuities across primate brain circuitry (e.g., Balezeau et al., 2020; Becker et al., 2022) or vocal and auditory systems (e.g. Boë et al., 2017; Jarvis, 2019; Wilson et al., 2017), the research on gestural communication in apes and monkeys has historically shown a significant interest within this evolutionary framework.

A large body of nonhuman primate studies has documented some continuities of the communicative gestural system with several key features of human language such as intentionality, referentiality, learning flexibility, and lateralisations (e.g. Tomasello, 2008; Meguerditchian and Vauclair, 2014; Molesti et al., 2020). About manual lateralisations specifically, studies in baboons and great apes have indeed shown that communicative manual gesturing elicited stronger right-hand use in comparison to non-communicative manipulative actions at a populational-level (reviewed in: Meguerditchian et al., 2013). In addition, at the individual level, a double dissociation concerning the type of handedness has been documented between gestural communication and object manipulation, showing that primates classified as right-handed for communicative gesture are not essentially classified as right-handed for object manipulation and vice versa (Meguerditchian and Vauclair, 2006). Those behavioural findings in different primate species suggest a specific laterised system for communicative gestures, which might be different from the one involves in handedness for object manipulation. This is consistent with human literature showing that typical object-manipulation handedness measures turned out to be a rather poor marker of language lateralisations (Fagard, 2013), as most left-handers (78%) also show left-hemisphere dominance for language (Knecht et al., 2000; Mazoyer et al., 2014), just like right-handed people. In both humans and nonhuman primates, direction of handedness for object manipulation was found associated to contralateral asymmetries of the motor hand area within the Central sulcus (e.g. humans: Amunts et al., 2000; Cykowski et al., 2008; chimpanzees: Hopkins and Cantalupo, 2004; Dadda et al., 2006; Baboons: Margiotoudi et al., 2019; Capuchin monkeys: Phillips and Sherwood, 2005; Squirrel monkeys: Nudo et al., 1992). In fact, it has recently been demonstrated that the neural substrates of typical handedness measures and language brain organisation might be not related but rather independent from each other (Groen et al., 2013; Ocklenburg et al., 2014; Häberling et al., 2016; Labache et al., 2020).

Whether gestural communication’s handedness in humans is a better predictor of language lateralisations and is thus different than typical handedness measures remain unclear. Nevertheless, several studies in humans are supporting this hypothesis. In early human development, the degree of right-handedness for preverbal gestures is more pronounced at a populational-level than handedness for manipulation (Blake et al., 1994; Bonvillian et al., 1997; see also Fagard, 2013; Cochet and Vauclair, 2010) and increases when the lexical spurt occurs in children contrary to manipulation handedness (Cochet et al., 2011). Moreover, further work showed Broca’s activation in the left hemisphere also for sign language production including manual and oro-facial gestures (Emmorey et al., 2004; MacSweeney et al., 2008).

Given such potential lateralisations links between gesture and language in humans, it is thus not excluded that the specific lateralisations’s signature found for communicative gestures in nonhuman primates might reflect evolutionary continuities with frontal hemispheric specialisation for speech/gesture integration. This hypothesis might be relevant to investigate given brain studies in nonhuman
primates have shown gross left-hemispheric asymmetries of homologous language areas at a population level that are similar to the ones described in humans (e.g., Geschwind and Levitsky, 1968; Keller et al., 2009): In particular Broca’s homologue in great apes (Cantalupo and Hopkins, 2001; Graic et al., 2020) as well as the Planum Temporale in great apes and even in baboons, an Old World monkey species, in both adult and newborns (Gannon et al., 1998; Marie et al., 2018; Becker et al., 2021a; Becker et al., 2021b).

For Old World monkeys specifically, no study regarding structural asymmetry for Broca’s homologue has been investigated. One reason is that determining this area in monkeys is particularly challenging in comparison to apes. In fact, the inferior precentral sulcus, the inferior frontal sulcus and the fronto-orbital sulcus, which are common borders of Broca’s homologue in apes (Cantalupo and Hopkins, 2001), are absent in monkeys and thus delimitation is not trivial. Nevertheless, all the detailed cytoarchitectonic studies addressing the Broca’s homologue within the frontal lobe in Old World monkeys (i.e. in mostly macaques but also in baboons) – and its two components Area 44 and 45 – pointed towards the same sulcus of interest as the epicentre of this region: the mid-ventral and ventral portion of the Inferior Arcuate sulcus (IA sulcus). The IA sulcus is considered homologue to the ascending branch of the inferior precentral sulcus (Amiez and Petrides, 2009) that delimits Broca’s area posteriorly in humans and great apes. In monkeys, Area 45 homologue sits in the anterior bank of the ventral IA sulcus (Petrides et al., 2005). In contrast, Area 44 homologue might be located in the fundus and the posterior bank of the ventral IA sulcus in monkeys (Petrides et al., 2005), which overlaps with F5 region related to the mirror neuron system (Belmalih et al., 2009; Rizzolatti and Fogassi, 2014). Electric stimulation in the fundus of the ventral IA sulcus elicited oro-facial and finger movements in macaques (Petrides et al., 2005). Concerning baboons specifically, a cytoarchitectonic study (Watanabe-Sawaguchi et al., 1991) showed similarities to the macaque frontal lobe organisation given Area 45 anteriorly to the IA sulcus, even if Area 44 was not described (Petrides et al., 2005; Belmalih et al., 2009; Rizzolatti and Fogassi, 2014; Watanabe-Sawaguchi et al., 1991). Therefore, in the absence of the usual Broca’s sulcal borders found in apes, the depth of the ventral part of the IA sulcus constitutes the only critical neuroanatomical marker for delimiting the border and the surface of Broca’s homologue in monkeys.

In sum, within the framework of the origin of hemispheric specialisation for language, most comparative works in nonhuman primates focused on population-level asymmetry for either brain or communicative behaviours. Those studies have reported similar population-level leftward brain asymmetry for key language homologue regions (Gannon et al., 1998; Cantalupo and Hopkins, 2001; Marie et al., 2018; Becker et al., 2021a; Becker et al., 2021b; Becker and Meguerditchian, 2021) or similar populational-level right-handedness for communicative gestures (reviewed in: Meguerditchian et al., 2013). Nevertheless, to test potential phylogenetic continuities, this approach suffered from lack of studies investigating the direct behavioural/brain correlates at the individual-levels.

In the present in-vivo MRI study conducted in 50 baboons (Papio anubis), we have (1) measured the inter-hemispheric asymmetries of the IA sulcus’ depth – from its dorsal to its most ventral portion among subjects for which the Central sulcus depth measure was available from a previous study (Margiotoudi et al., 2019) (2) as well as its potential links with direction and degree of communicative gesture’s handedness in comparison to handedness for manipulative actions as measured with a bimanual tube task (see Hopkins, 1995). In other words, we tested specifically whether the depth asymmetry of the most ventral Inferior Arcuate sulcus’ portion (ventral IA sulcus, i.e. the Broca’s homologue) – but not the Central sulcus – was exclusively associated with communicative gestures’ lateralisation.

Results
Between baboons communicating preferentially with the right hand versus the ones with the left hand, we found significant contralateral differences of depth asymmetries in the ventral portion of the IA sulcus (i.e., from the mid-ventral IA position to the most ventral IA sulcus portion, namely from contiguous positions 65–95 out of the 99 segmented positions of the entire IA sulcus) according to a cluster-based permutation test ($p < .01$, t-value clustermass $= 76.16$, for $p < .01$ a clustermass of 65.28 was needed, see Marie and Oostenveld, 2007). In other words, the 28 baboons using preferentially their right hand for communicative gestures showed more leftward IA sulcus depth asymmetry at this cluster than the 22 ones using preferentially their left-hand. In contrast, for non-communicative
manipulative actions, we found no significant difference of sulcus depth asymmetries between the left- (N = 22) versus right-handed (N = 28) groups concerning any portion of the IA sulcus, according to a cluster-based permutation test (p > .10) (Figure 1).

In addition, after calculating the AQ score per subject representing the sulcus depth asymmetry of the whole ‘Broca’s cluster’ (i.e. from the sum of the IA sulcus depths from positions 65–95 in the left hemisphere and the sum of IA sulcus depths from position 65–95 in the right hemisphere), we found a significant negative correlation between individual AQ depth values of the Broca’s cluster (i.e. from positions 65–95) and individual handedness degree for communication (HI): \( r(48) = -0.337; p < .05 \) (i.e. the stronger the hand preference is for one hand, the deeper is the IA sulcus asymmetry from positions 65 to 95 in the contralateral hemisphere) (Figure 2A). In contrast, AQ depth values of the Broca’s cluster did not show significant correlation with HI for non-communicative actions (\( r(48) = -0.037; p = 1 \)) (Figure 2B). Using the cocor package in R (Diedenhofen and Musch, 2015), a comparison between
these two overlapping correlations based on dependent groups showed a significant difference between the two correlations (p < .05).

When comparing with the control sulcus of interest, the Central sulcus related to the primary motor cortex, an opposite effect was found between handedness for manipulative actions and hand preferences for communicative gesture. We found no significant difference of sulcus depth asymmetries regarding communicative gestures. In contrast, Margiotoudi et al., 2019 reported that the CS presented a contralateral asymmetry at continuous positions 56–60 (labelled as the ‘Motor-hand area’s cluster’) for non-communicative manipulative actions, after permutation tests for correction (Figure 1).

Finally, we conducted a mixed-model analysis of variance with AQs depth values for the IA sulcus ‘Broca’s cluster’ and for the Central sulcus ‘Motor hand area’s cluster’ (AQ derived from continuous positions 56–60, see Margiotoudi et al., 2019) serving as the repeated measure while communicative handedness (left- versus right-handed) and action handedness (left- versus right-handed) were between-group factors. The mixed-model analysis of variance demonstrated a significant main effect on the AQ scores for communication handedness (F1,46 = 14.08, p < .01) and for action handedness (F1,46 = 4.1, p < .05).

Discussion
The results of the study are straightforward. We showed that the IA sulcus left- or rightward depth asymmetry at its mid-ventral and ventral portion (labelled as the ‘Broca cluster’) is associated exclusively with contralateral direction (left-/right-hand) of communicative manual gestures’ lateralisation in baboons but not handedness for non-communicative actions. Building upon these first results, we also found a significant negative correlation between the Handedness Index (HI) values for communicative gestures and the Asymmetric Quotient (AQ) depth values of the IA sulcus ‘Broca’s cluster’, suggesting that the contralateral links between handedness for gestural communication and depth asymmetries at the most ventral portion of the IA sulcus is evident not only at a qualitative level but also at a quantitative level as well. In other words, individuals with a stronger degree of manual lateralisation for communicative gesture have greater IA sulcus depth asymmetries at this ventral cluster.
in the hemisphere contralateral to their preferred hand for communication. The ventral positions of such sulcal depth asymmetries are clearly at a crossroad of Broca-related frontal regions including the fundus of the sulcus, Area 44 (Petrides et al., 2005), the anterior bank, Area 45 (Petrides et al., 2005), the posterior bank and ventral Fs or granual frontal area (GF) (Belmalih et al., 2009; Rizzolatti and Fogassi, 2014). Since the sulcus’ depth might reflect a gyral surface and its underlying grey matter volume, future work of delineating and quantifying grey matter of the ventral IA sulcus would help determining which of those sub-regions of the Broca homologue is driving the asymmetry specifically, for instance by VBM methods.

Whereas handedness for manipulative actions in baboons was previously found related to the motor cortex asymmetry within the Central sulcus (Margiotoudi et al., 2019), our present findings report the first evidence in monkeys that the neurostructural lateralisation’s landmark of communicative gesture is located in a frontal region, related to Broca’s homologue. Such a contrast of results between manipulation and communication found at the cortical level is consistent with what was found at the behavioural level in studies showing that communicative gesture in baboons and chimpanzees elicited specific and independent patterns of manual lateralisation in comparison to non-communicative manipulative actions (Meguerditchian and Vauclair, 2009; Meguerditchian et al., 2010). Therefore, it provides additional support to the hypothesis suggesting that gestural communication’s lateralisation in nonhuman primates might be, just as language brain organisation in human (see Häberling et al., 2016), related to a different lateralised neural system than handedness for pure manipulative action. Its specific correlates with Broca’s homologue’s lateralisation is also consistent with what was found in our closest relatives, the chimpanzee (Taglialatela et al., 2006; Meguerditchian et al., 2012).

Regarding Broca’s area in humans, very recently, a functional segregation was proposed with Broca’s anterior part implicated in language syntax and its posterior part exclusively implicated in motor actions (Zaccarella et al., 2021). The authors argued that action and language meet at this interface. In an evolutionary perspective we propose therefore that the intentionality of primate’s communicative gesture might account for this hypothesised functional interface of actions and language prerequisites, nested inside the monkeys’ Broca’s homologue (see also: Rizzolatti and Craighero, 2004Arbib et al., 2008; Rizzolatti and Fogassi, 2014; Corballis, 2015). In addition, in macaques Broca’s homologue, neuronal recordings showed populations of specific neurons activated for both volitional vocal and manual actions (Gavrillov and Nieder, 2021).

The articulation of our results with this recent literature suggests that gestural communication may be a compelling modality for one of the multimodal evolutionary roots of the typical multimodal language system in humans and its hemispheric specialisation. It is thus not excluded that language-related frontal lateralisation might be much older than previously thought and inherited from a gestural communicative system dating back, not to Hominid origins, but rather to the common ancestor of humans, great apes and Old World monkeys, 25–35 million years ago.

**Materials and methods**

**Subjects**

Inter-hemispheric asymmetries of the IA sulcus’ depth were quantified from anatomical T1w MRI images in 80 baboons *Papio anubis* born in captivity and free from developmental or anatomical abnormalities or brain disorders (generation F1, 52 females, 28 males, age range = 7–32 years, mean age (years): M = 17.7, SE = 5.9). Out of this sample, were included only subjects which overlaps with both (1) the sample of subjects for which individual measures of handedness for communicative gestures were available (i.e. hand slapping gesture, Meguerditchian and Vauclair, 2006) and (2) the previous sample of 63 subjects (i.e. 35 right-handed and 28 left-handed) reported in Margiotoudi et al., 2019 for which both Central sulcus depth measures and individual measures of handedness for manipulative actions (i.e. the bimanual tube task, Vauclair et al., 2005) were reported. It resulted a total overlap of 50 baboons (29 females and 21 males, mean age (years): M = 12.3, SE = 5.8) who combined thus the both types of measures of handedness (communication versus manipulation) and the depth measures of the two sulci of interest (IA sulcus and Central sulcus) in the two hemispheres of the brain.
All baboons were housed in social groups at the Station de Primatologie CNRS (UPS 846, Rousset, France; Agreement number for conducting experiments on vertebrate animals: D13-087-7) and have free access to outdoor areas connected to indoor areas. Wooden and metallic, ethologically approved, structures enrich the enclosures. Feeding times are held four times a day with seeds, monkey pellets and fresh fruits and vegetables. Water is available ad libitum. The study was approved by the ‘C2EA-71 Ethical Committee of Neurosciences’ (INT Marseille) under the number APAFIS#13553–201802151547729. The experimental procedure complied with the current French laws and the European directive 86/609/CEE.

**Sulcal parametrization**

The IA sulcus and the Central sulcus were extracted from T1w images using the pipeline of the free BrainVisa software (see Mangin et al., 2004 for details of the procedure). The sulcus parametrization tool within the BrainVisa toolbox provides therefore sulcus-based morphometry by subdividing the sulci of each hemisphere into 99 standardized positions from dorsal to ventral sulci extremities in order to quantify the variation of sulcal depth all across the sulci’s 99 positions (Mangin et al., 2004). This automatic algorithm is free from observer’s judgment. To estimate asymmetries of the sulci’s depth between the two hemispheres an asymmetry quotient (AQ) for each of the 99 sulcal positions AQ = (R – L) / (R + L × 0.5) was computed (Margiotoudi et al., 2019). The AQ values vary between −2 and +2 with positive values indicating right-hemispheric lateralisation and negative values indicating left-hemispheric lateralisation.

**Behaviour correlate**

For further investigating its potential behavioural correlates, we tested whether the right- versus left-handed groups classified for a given manual task (i.e. gestural communication versus manipulative actions) differed in term of neurostructural depth asymmetries (AQ) within the IA sulcus and the Central sulcus. The two types of handedness measures were previously collected (for communicative gesture: Meguerditchian and Vauclair, 2006; Meguerditchian et al., 2011 for manipulative actions: Vauclair et al., 2005; Molesti et al., 2016).

Communicative gesture was defined as a movement of the hand directed to a specific partner or audience in order to affect its behaviour (Molesti et al., 2020). Like in apes, some communicative manual gestures in baboons have been found to share human-like intentional control, referential properties, flexibility of acquisition and of use as well as similar specific pattern of manual lateralisation (reviewed in Tomasello, 2008; Meguerditchian and Vauclair, 2014; Meguerditchian et al., 2013). The present study focused specifically on the ‘Hand slapping’ gesture which was previously found optimal for measuring gestural communication’s lateralisation in this species (Meguerditchian and Vauclair, 2006; Meguerditchian et al., 2011). Indeed, the hand slapping behaviour – a probably innate gestures used by the baboon to threat or intimidate the recipient – is the most common and frequent visual gesture of the repertoire (Molesti et al., 2020) produced intentionally and unimanually in a lateralised manner across similar agonistic contexts and similar emitter’s postures (Meguerditchian et al., 2013). Hand use was recorded in a baboon when slapping or rubbing quickly and repetitively the hand on the ground in direction to a conspecific or a human observer at an out of reach distance. Recorded events were taken from different bouts and not repeated measures from the same bout. As Margiotoudi et al., 2019, in case a subject has been assessed in multiple sessions within 2004–2015, the final classification as right or left-handed was selected based on the session with the most observations, excluding subjects with less than five observations (Mean = 25.98, S.E. = 3.67).

Handedness for manipulative actions was assessed using the well-documented bimanual coordinated ‘Tube task’ (Hopkins, 1995). Hand use was recorded when extracting food with a finger out of a PVC tube hold by the other hand.

The individual handedness index (HI) for a given manual behaviour, or degree of individual manual asymmetry, was calculated based on the formula (#R−#L)/(#R+#L), with #R indicating right hand responses and #L for left hand responses. The HI values vary between −1 and +1 with positive values indicating right hand preference, negative values indicating left hand preference and 0 indicating no preference. The absolute HI score indicate the strength of manual preference.

Among the 50 baboons, for communicative gesture, 22 subjects were thus classified as left-handed, 28 as right-handed following the HI direction. A 51st subject, having a HI score of 0 (i.e. no manual
bias), could not be classified in either categories and has been thus excluded from the study. For object-related manipulative actions (i.e. the bimanual tube task), 22 subjects were classified as left-handed, 28 as right-handed as already reported in Margiotoudi et al., 2019 for those 50 overlapping subjects. Among the 50 baboons, 18 subjects switched left-/right-handed categories of hand preference between communicative gesture and manipulative actions (i.e. 9 from left-handed group for gestural communication to right-handed group for manipulative actions, 9 from right-handed group for gestural communication to left-handed group for manipulative actions).

**Statistical analysis**

Statistical analysis was conducted using R 3.6.1 by Cluster Mass Permutation tests (Maris and Oostenveld, 2007). First, an assembly of depth asymmetry measures was defined as a ‘cluster’ when continuous significant differences of the same sign across positions were found between groups (two-sided t-tests, Welch corrected for inequality of variance, p < .05). Second, the sum of t-values within each cluster was calculated (the ‘cluster mass’). Next, permutations were conducted for the between individual tests: For a given type of manual behaviour, Left-handed individuals’ AQ values versus Right-handed individuals’ AQ values were randomly redistributed between individuals and the maximum absolute cluster mass was calculated for each randomly permuted set. This procedure was repeated 5000 times and the 99% confidence interval (CI) of the maximum cluster mass was calculated. The clusters in the observed data were considered significant at 1% level if their absolute cluster mass was above the 99% CI of the distribution (i.e. p < .01).

We also performed a linear correlation between (1) the Handedness Index (HI) values for communicative gesture calculated from the 50 individuals and (2) the Asymmetric Quotient (AQ) values of those 50 baboons calculated from the respective left and right ventral IA sulcus’ depth sum of the continuous positions of the cluster for which a significant difference in AQ score is detected by t-test comparison between the right- and left-handed groups. The same procedure was followed for the HI values for non-communicative actions for those 50 individuals.

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Author contributions
Yannick Becker, Data curation, Formal analysis, Writing - original draft; Nicolas Claidière, Damien Marie, Data curation, Formal analysis; Konstantina Margiotoudi, Formal analysis; Muriel Roth, Resources, designed MRI sequences; Bruno Nazarian, Resources, designed the baboons’ monitoring programs; Jean-Luc Anton, Resources, coordinated the MRI sessions; Olivier Coulon, Methodology, Resources, Software, Writing - review and editing, designed the sulcus parametrization tool; Adrien Meguerditchian, Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing - original draft, Writing - review and editing, supervised the MRI acquisitions

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Ethics
All baboons were housed in social groups at the Station de Primatologie CNRS (UPS 846, Rousset, France; Agreement number for conducting experiments on vertebrate animals: D13-087-7) and have free access to outdoor areas connected to indoor areas. Wooden and metallic, ethologically approved, structures enrich the enclosures. Feeding times are held four times a day with seeds, monkey pellets and fresh fruits and vegetables. Water is available ad libitum. The study was approved by the “C2EA-71 Ethical Committee of Neurosciences” (INT Marseille) under the number APAF-IS#13553-201802151547729. The experimental procedure complied with the current French laws and the European directive 86/609/CEE.

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Additional files
Supplementary files
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Data availability
The behavioural, neuro-anatomical and statistic code data that support the findings of this study are available in “OSF Storage” with the identifier [https://doi.org/10.17605/OSF.IO/DPXS5]. [https://osf.io/dpxs5/?viewonly=f406ad972edd43e485e5e4076bae0f78].

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References


7. Chapter: The Arcuate Fasciculus disentangled: Different conceptions are depicting different evolutionary trajectories

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The Arcuate Fasciculus and language origins: Disentangling existing conceptions that influence evolutionary accounts

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- Nonhuman primate

\textbf{ABSTRACT}

The Arcuate Fasciculus (AF) is of considerable interdisciplinary interest, because of its major implication in language processing. Theories about language brain evolution are based on anatomical differences in the AF across primates. However, changing methodologies and nomenclatures have resulted in conflicting findings regarding interspecies AF differences: Historical knowledge about the AF originated from human blunt dissections and later from monkey tract-tracing studies. Contemporary tractography studies reinvestigate the fasciculus’ morphology, but remain heavily bound to unclear anatomical priors and methodological limitations. First, we aim to disentangle the influences of these three epistemological steps on existing AF conceptions, and to propose a contemporary model to guide future work. Second, considering the influence of various AF conceptions, we discuss four key evolutionary changes that propagated current views about language evolution: 1) frontal terminations, 2) temporal terminations, 3) greater Dorsal- versus Ventral Pathway expansion, 4) laterality. We conclude that new data point towards a more shared AF anatomy across primates than previously described. Language evolution theories should incorporate this more continuous AF evolution across primates.

\textbf{1. Introduction}

The Arcuate Fasciculus (AF), or the archel/curved bundle in Latin, is traditionally regarded as one of the major language pathways in the human brain: It arches around the Sylvian or lateral fissure to connect the key speech production region (Broca’s area) in the frontal lobe, with the speech comprehension region (Wernicke’s area) in the posterior temporal lobe (Geschwind, 1970). Congruent with Geschwind’s influential model, decades of subsequent research have generally converged on the AF’s critical involvement in language and speech functions (e.g., Catani and Mesulam., 2008; Catani and Thiebaut de Schotten., 2012; Dick and Tremblay., 2012). Interestingly, the anatomical homologue of this critical white matter pathway for human language exists in the nonhuman primates, where language is absent (e.g., Eichert et al., 2019; Frey et al., 2014; Rilling et al., 2008, 2012). This crucial phylogenetic link provides a valuable avenue to probe the evolutionary origins of human language i.e., by comparing how the AF differs across humans and nonhuman primates. Indeed, in the past decade, the emergent field of nonhuman primate or comparative magnetic resonance imaging (MRI) neuroimaging (Friedrich et al., 2021; Milham et al., 2020) has enabled detailed anatomical and functional comparisons of the AF across humans and various nonhuman primate species, such as the macaque monkey and the chimpanzee (e.g., Balezeau et al., 2020; Mars et al., 2021; Rilling et al., 2008, 2012; Rocchi et al., 2021; Wilson et al., 2015). The overarching aim of this review is to synthesize this exciting new body of work that compares the anatomy and function of the AF in humans versus nonhuman primates, to understand how the Arcuate Fasciculus might, or might not, have changed across primate evolution to

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\footnotesize{Abbreviations: AF, Arcuate Fasciculus; SLF, Superior Longitudinal Fasciculus; MdLF, Middle Longitudinal Fasciculus; dMRI, diffusion magnetic resonance imaging; NHP, Nonhuman primate.}
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support the emergence of language in humans.

In the first part of this review, we tackle a major challenge that confronts present-day researchers seeking to investigate the AF: There is currently poor consensus about the anatomical definition of the AF (e.g., where it terminates in the frontal and temporal lobes), and its nomenclature (e.g., whether it is considered part of, or distinct from the Superior Longitudinal Fasiculus (SLF) or Middle Longitudinal Fasiculus (MdLF)). This is primarily driven by the fact that, since its discovery, the methodologies used to study and delineate the AF (e.g., blunt dissections, diffusion MRI tractography, neural tract-tracing) have been constantly evolving, resulting in different descriptions and naming of the AF (e.g., Oliveira et al., 2021; Vavassori et al., 2021). As such, we start the current review with an overview of how the definition and nomenclature of the AF have evolved along with the emergence of different methodologies in the field. This overview, in disentangling the various existing conceptions of the AF, aims to provide a contemporary definition of the fibre bundle that will guide our subsequent review of existing comparative studies of the primate AF.

The second part of this review will discuss four key findings from recent comparative research that shed light on the question about how the AF has changed in humans relative to nonhuman primates: 1) An expansion of the AF’s fronto-temporal terminations into the inferior frontal cortex (e.g., Schmahmann and Pandya, 2006); 2) An expansion of the AF’s temporal terminations beyond the middle temporal cortex (e.g., Eichert et al., 2019); 3) A greater expansion of the Dorsal Language Pathway (which includes the AF), relative to the Ventral Language Pathway (e.g., Rilling et al., 2008; Balezeau et al., 2020); and 4) An absence of lateralisation in the monkey’s AF (e.g., Balezeau et al., 2020). For each finding, we will discuss how the different conceptions of the AF have led to different views on these questions, and subsequently influenced theorisations about the evolution of language. We will conclude that the collective data point towards a continuity in AF anatomy across primates. Last but not least, this review will open a discussion regarding the existing questions and future directions in the field.

2. Part I: Disentangling existing conceptions of the arcuate Fasciculus

Differing anatomical descriptions and nomenclatures of the Arcuate Fasciculus (AF) fibre bundle have surfaced since its initial discovery by Reil in 1809 (see Catani et al., 2010; Dick and Tremblay., 2012; ef. Oliveira et al., 2021; Vavassori et al., 2021 for historical reviews of the AF). To a large extent, the various conceptions result from the various emerging methodologies used to investigate the AF, including post-mortem brain dissections, neural tract-tracing, and more recently, diffusion magnetic resonance imaging (dMRI) tractography. Here, we briefly trace the emergence of various conceptions of the AF, relating them to the methods employed to investigate the tract, to finally arrive at a contemporary definition of the AF to guide our subsequent review of the comparative AF literature.

2.1. Early 19th to late 20th century: Post-mortem blunt dissections and the synonymy between Arcuate Fasciculus (AF) and Superior Longitudinal Fasciculus (SLF)

Post-mortem blunt dissection was the first methodology adopted to investigate the Arcuate Fasciculus (AF). The method briefly involves first, the post-mortem extraction and fixation of the brain, followed by the use of a blunt dissection tool to meticulously peel away the grey and white matter progressively to reveal the extents of the various axon bundles. The blunt dissection method was the dominant method employed throughout the 19th century to study human neuroanatomy and had led to many seminal works and discoveries of that era (e.g., Burdach, 1822; Dejerine and Dejerine., 1895; Meynert, 1885; Klinger, 1935). While this technique enabled the identification of distinct white matter bundles and their individual courses in the brain, they were limited in 1) making distinctions between axon bundles that run in parallel, or that overlap or cross in their courses; and 2) determining the precise axonal origins and terminations of the bundles (Petrides, 2014; Yaşargil et al., 2004).

Indeed, it was through blunt dissections that Johann Christen Reil, in 1809, first discovered the system of longitudinal white matter fibres that arched along the Sylvian (or lateral) fissure to interconnect the frontal, parietal and temporal cortices (Fig. 1). Using the same method, Friedrich Burdach further characterised and first named these long arching fibres as the “Bogenbündel” in German, which translates to the “arched bundle” or arcuate fasciculus in Latin (Burdach, 1826). For most of the 19th century, two nomenclatures – “Arcuate Fasciculus (AF)” and “Superior Longitudinal Fasciculus (SLF)” – were synonymously used by the most prominent neuroanatomists to describe the longitudinal frontal-parieto-temporal fibre bundle (Catani et al., 2010; Dick and Tremblay., 2012). For instance, while Meynert (1885) used the term AF, Wernicke (1874) and Dejerine (Dejerine and Dejerine., 1895) used both AF and SLF to refer to the same longitudinal fibre bundle. The interest for the SLF/AF fibre bundle rose to prominence at the start of the 20th century as Wernicke (Wernicke, 1908) identified it as one of two main associative fibre systems for language. Notably, in Geschwind’s influential neurological model of language (Geschwind, 1970), the term AF, and not the term SLF, was used to depict the fibre system linking the language production centre (inferior frontal cortex) to the language comprehension centre (posterior middle temporal cortex). Since then, the label AF had received an increased recognition and usage to refer to

![Fig. 1. Classic dissection derived AF/SLF Model (e.g., Reil, 1809; Burdach, 1822; Dejerine, 1895) in the human brain. In this model, the names AF and SLF are both used to refer to the same bundle of fronto-temporal longitudinal fibres. AF: Arcuate Fasciculus; SFS = Superior Frontal Sulcus; SpFs = Superior Pre-central Sulcus; IPS = Inferior Pre-central Sulcus; IFS = Inferior Frontal Sulcus; AS = Ascending branch of Sylvian Fissure; HS = Horizontal branch of Sylvian Fissure; IPS = Intra-Parietal Sulcus; Tpt = Temporal-parietal area (BA22); aSMG = anterior Supra-Marginal Gyrus (BA40); pSMG = posterior Supra-Marginal Gyrus (BA40); ANG = Angular Gyrus (BA39); SPL = Superior Parietal Lobule (BA7).](image-url)
the classical language pathway (more than the term SLF), even though the terms AF and SLF are generally referred to the same tract bundle until the late 20th century (Fig. 1).

From the turn of the 20th century until today, two other methodologies were adopted, alongside blunt dissections (see Dziedzic et al., 2021 for a recent review on dissections with the Klinger technique), to investigate the Arcuate Fasciculus bundle: neural tract-tracing and diffusion MRI (dMRI) tractography. These techniques have led to distinguish the classic AF/SLF longitudinal fibre bundle into different constituent bundles with distinct courses and terminations. However, due to the differences between the two methods, various models of the AF/SLF fibre system had emerged. Here, we briefly describe each method and its associated models and conceptions of the AF/SLF fibre system.

2.2. Late 20th Century: Neural tract-tracing reveals distinctions between the AF and SLF fibre systems

Neural tract-tracing is a precise, but also highly invasive method for studying brain connections (see Lanciego and Wouterlood, 2020; Saleeba et al., 2019 for recent reviews about the tract-tracing methodology). Briefly, it involves the injection of anatomical tracers into a living brain, which would be transported from the injected region to other regions via interconnecting axons, followed by histological analyses of the brain ex-vivo to visualise the axons and their terminations that have been labelled by the injected tracers. Depending on whether a retrograde or anterograde tracer was administered, the brain region that sends projections into the injected region or the brain region that receives projections from the injected region along with the interconnecting axons, will be labelled, respectively. Hence, using a combination of retrograde and anterograde tracing, the origins and terminations of cortico-cortical connections associated with a brain region of interest can be precisely determined. As such, contrary to blunt dissection and dMRI tractography, tract-tracing possesses the resolution to distinguish between fibre bundles that overlap or cross in their courses but have different terminations and can therefore also define a monosynaptic connection. Thus, it is commonly regarded as the gold-standard technique for studying brain connections. A key drawback, however, is that tract-tracing is currently only performed in few nonhuman primate subjects due to its invasive nature, which requires the euthanasia of the animal.

Tract-tracing was employed in a series of important studies that resulted in the dissociation of the classical AF/SLF longitudinal fibre system (Fig. 1) into several distinct fibre bundles based on their origins and terminations in the macaque brain (Frey et al., 2014; Petrides and Pandya, 1984, 1988, 2006, 2009; Schmahmann et al., 2007; Schmahmann and Pandya, 2006; Schmahmann and Pandya, 2006). SLF I, II, III = First, second and third branch of the Superior Longitudinal Fasciculus, AF = Arcuate Fasciculus; IArS = Inferior Arcuate Sulcus, PS = Principal Sulcus; CS = Central Sulcus; IPS = Intra-Parietal Sulcus; STS = Superior Temporal Sulcus; PP; PFm; PFG; PG are cytoarchitectonic labels for the parietal areas based on (von Economo and Koskinas, 1925).

which are further distinguished in three different branches I, II and III (Fig. 2).

2.3. Towards a contemporary conception of the AF: diffusion MRI tractography

Diffusion MRI (dMRI) tractography is, at present, the only technique available to investigate white matter fibre pathways both in-vivo and ex-vivo, across a large sample of individuals. It involves a form of magnetic resonance imaging that measures the diffusivity of water molecules in the brain. Since water diffusion in the brain is highly constrained by axons (i.e., water tends to flow along the direction of the axons), by tracking the most probable directions of water diffusion voxel-by-voxel, one would be able to reconstruct the main fibre pathways that course between two specific areas in the brain. Alternatively, even the total pathways between all areas in the brain can be reconstructed, yielding a so-called whole-brain tractogram. Note that these reconstructed pathways are essentially “streamlines” that connect vectors of water diffusion computed in each brain voxel and might not necessarily depict true axonal connections. Therefore, tractograms notoriously contain a large number of false positive (Maier-Hein et al., 2017). This is especially so when there are multiple crossing fibres passing within a single voxel, which makes it notoriously difficult to determine the actual orientation of fibres (Girard et al., 2020). Additionally, dMRI tractography does not reveal whether a connection is monosynaptic (single axon from origin to termination sites) or polysynaptic (more than one axon interconnecting between origin and termination sites). Due to the limitations in disentangling the various association pathways that pass through the frontal and parietal-temporal regions (i.e., AF, SLF I, II, III), most dMRI studies therefore collectively refer to these tracts as the “Dorsal language Pathway or stream” (e.g., Saur et al., 2008). On the other hand, a second set of pathways that curves ventrally from the inferior prefrontal cortex, across the Sylvian fissure, to the anterior and middle temporal cortex are collectively known as the “Ventral language Pathway or stream”. This division emulates the well-known visual pathway division (Hickok and Poeppel, 2004). Functionally, the Dorsal Pathway is involved in mapping sound to articulation, while the Ventral Pathway is involved in...
mapping sound to meaning (Hickok and Poeppel, 2004; Saur et al., 2014). Potential correspondences between figures are displayed. SLF I, II, III = First, second and third branch of the Superior Longitudinal Fasciculus, AF = Arcuate Fasciculus; SFS = Superior Frontal Sulcus; SPrS = Superior Precentral Sulcus; IPS = Inferior Precentral Sulcus; IFS = Inferior Frontal Sulcus; AS = Ascending branch of Sylvian Fissure; HS = Horizontal branch of Sylvian Fissure; PFS = Posterior Fissure; SPS = Superior Parietal Sulcus; IPrS = Inferior Parietal Sulcus; Tpt = Temporal-parietal area (BA22); aSMG = anterior Supra-Marginal Gyrus (BA40); pSMG = posterior Supra-Marginal Gyrus (BA40); ANG = Angular Gyrus (BA39); SPL = Superior Parietal Lobule (BA7).

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and are also highlighting the importance of the Dorsal Pathway in semantics and the production of meaningful words or speech, respectively. The first conception, which was proposed by Catani and colleagues using dMRI tractography (Catani et al., 2005), is based on priors from classical dissection studies (Fig. 3 left panel). This conception names the peri-sylvian longitudinal fibres (both arching and non-arching) collectively as the AF, and divides it into three distinct segments: 1) a long direct segment that connects the posterior part of the superior temporal gyrus (Wernicke’s area) to the inferior frontal cortex (Broca’s area); 2) an anterior indirect segment that connects Broca’s area and inferior (Geschwind’s territory) parietal cortices; and 3) a posterior indirect segment that links the inferior parietal cortices with the Wernicke’s area. This model was obtained via a two-regions-of-interest (ROI) “virtual dissection” approach using diffusion tractography (Catani et al., 2002). First, one ROI was defined that delineated the main body of the AF identified on the fractional anisotropy (FA) image. Next, two other ROIs were defined in the inferior frontal cortex and posterior superior temporal cortex respectively. Fibres were then tracked between each pair of ROIs which yielded the three segments of the AF. Note that the placement of ROIs was strongly influenced by Geschwind’s model of the language system (Geschwind, 1970) that proposed a pathway, which was termed the AF, linking Broca’s and Wernicke’s language areas in the brain. Indeed, this 3-segment AF model was consistent with neurological models of aphasia and evidence from aphasic patients (e.g., Damasio and Geschwind, 1984), where the long direct pathway (frontal-temporal) is associated with phonological-related language processes (e.g., rapid word repetitions that do not involve semantic retrieval processes); while the indirect anterior (frontal-parietal) and posterior (parietal-temporal) pathways are associated with semantic-related language processes, such as speech comprehension and the production of meaningful words or speech, respectively (Catani et al., 2005). Note that the tractography recipe of that model has been improved in recent years, including more than two ROIs (e.g., Forkel et al., 2014). Subsequently, this 3-segment AF model was also validated by other studies using human electrocorticography (Matsumoto et al., 2004), functional connectivity (Holland et al., 2007) and post-mortem dissections (Fernández-Miranda et al., 2008; Lawes et al., 2008).

A second conception comes from researchers who have reconstructed the longitudinal pathways with dMRI tractography based on anatomical priors from macaque tract-tracing experiments (Fig. 3 right panel) (e.g., Barbeau et al., 2020; Frey et al., 2008; Makris et al., 2009; Warrington et al., 2020). Considering that neural tract-tracing is the gold standard for determining the precise origins and terminations, and axonal courses of brain connections, the macaque model that separates the peri-sylvian longitudinal fibres into the AF, SLF I, II and III bundles (i.e., Frey et al., 2014) would constitute the most anatomically accurate model of the primate longitudinal fibre system at present (Fig. 3 right panel). Critically, it remains questionable how generalizable this macaque model is to the human brain, since after all language (which is associated with the AF) is not present in the macaque. One strategy, adopted by Petrides and colleagues (e.g., Frey et al., 2014; Petrides and Pandya, 1988, 2009), was to perform tract-tracing from macaque cortical regions whose human counterparts are known, based on cytoarchitectonics, which facilitates the macaque-human transfer of the anatomical findings. Indeed, by performing in-vivo dMRI tractography in the human brain using carefully defined anatomical landmarks that are known to be homologous to the macaque, recent researchers have been able to replicate the macaque AF, SLF I, II, III and MdLF fibre tracts in the human brain (e.g., Barbeau et al., 2020; Frey et al., 2008; Luo et al., 2020; Makris et al., 2009). Note that as defined by Luo et al. (2020) the MdLF “courses through the superior temporal gyrus (STG) and inferior parietal lobule (IPL) connecting STG (BA 22, 42) and temporal pole (TP, BA 38) principally with the angular gyrus (AG, BA 39). The MdLF is distinct from other long association fibre tracts connecting the frontal, parietal or temporal lobes such as the superior longitudinal fascicule II (SLF II) and SLF III or the arcuate fascicle (AF), respectively, and the extreme capsule (Makris et al., 2009)”. How then might we reconcile those two legitimate conceptions of the AF? A potential hypothesis is that “the long direct segment”, “the anterior indirect segment”, and “the posterior indirect segments” defined in the first conception might correspond to “the AF”, “the SLF II and/or III”, and “posterior part of the AF and the posterior part of the middle longitudinal fasciculus (MdLF); based on Petrides, 2014; see also e.g., Latini et al., 2021” as defined in the second conception respectively. This could be verified via a virtual dissection experiment using dMRI tractography to test whether it is possible to obtain the macaque-derived model of the AF from Catani’s model (i.e., first conception) using additional region-of-interests, since currently, the latter has been derived using a two-ROI, or three-ROI approach to detect each of the three segments (e.g., Catani et al., 2005; Forkel et al., 2014) (Box 1).
3. Part II: four questions about the evolution of the Arcuate Fasciculus across primates

Current comparative work has revealed four key findings about the unique evolution of the human AF anatomy, based on comparisons with macaques and chimpanzees. First, studies have proposed that the frontal cortical terminations of the AF have changed in the human brain (e.g., Schmahmann and Pandya., 2006). Second, studies have proposed that the temporal cortical terminations of the AF have expanded in the human brain (e.g., Eichert et al., 2019). Third, studies have proposed a greater Dorsal (which includes the AF) versus Ventral Pathway expansion across primate evolution (e.g., Rilling et al., 2008). Fourth, studies have proposed an absence of left-lateralisation in the monkeys AF, that is present in humans (e.g., Rocchi et al., 2021). Here, we will re-examine the evidence for these findings with respect to their AF conceptions and discuss their implications for language evolution theories.

3.1. Question 1: are AF terminations in the inferior frontal cortex (Broca’s area) present in the human, but not in the nonhuman primate brain?

Classically, the human AF connects to the Broca’s area in the inferior frontal cortex (Brodmann’s areas 44 and 45). These frontal regions are significant for language because they are involved in the high-level control of orofacial and vocal motor responses that are needed for language production (Loh et al., 2020). Direct AF connections to these frontal regions thus provide access to the key motor actions (e.g., articulation, facial expressions, gestures) needed for language expression in humans (Petrides and Pandya, 2009). Whether the same AF frontal projections exist in nonhuman primates (NHPs) is therefore a crucial question that would shed light on why language is processed only in humans. Currently, there are several theoretical accounts based on how a lack of AF frontal terminations in the nonhuman primate brain could explain the uniqueness of human language (e.g., Aboitiz and Garcia, 1997; Friederici, 2017; Pulvermüller, 2018; Schmahmann and Pandya, 2006). However, the most recent data from tract-tracing experiments (e.g., Frey et al., 2014) appear to contradict these accounts as AF connections to macaque areas 44 and 45 were demonstrated. Here, we carefully review past and present tract-tracing studies of the macaque peri-sylvian longitudinal fibre system to resolve the question about whether AF inferior frontal terminations exist in the macaque brain.

Based on the landmark tract-tracing investigation in the macaque brain, (Petrides and Pandya, 1988) had traced AF terminations into the dorsal part of the frontal cortex (dorsal areas 6, 8A and prefrontal area 46), but not to the inferior frontal cortex, where Broca’s area’s homologue lies. Instead, the inferior frontal cortex only connected to the parietal cortex via the SLF II and III. This result remained important in the field over the next two decades: it was included and reproduced in the highly influential atlas of fibre pathways of the macaque brain by Schmahmann and Pandya (Schmahmann and Pandya., 2006); see Fig 13–5 on pp 407 for a depiction of the AF and it served as the anatomical reference for several dMRI studies (e.g., Thiebaut de Schotten et al., 2012) (Fig. 5 Left panel). Critically, this discovery had led to several theoretical accounts suggesting that the change in AF’s frontal projections from dorsal part of the frontal cortex in nonhuman primates to Broca’s area in humans could explain the emergence of human language (e.g., Aboitiz and Garcia, 1997; Friederici, 2017; Pulvermüller, 2018; Schmahmann and Pandya, 2006). For instance, Schmahmann and Pandya (Schmahmann and Pandya., 2006) proposed that the macaque AF might not be a “language bundle” (pp 408) as it does not connect the homologues of Broca’s (inferior frontal cortex) and Wernicke’s areas (posterior superior temporal gyrus), but instead the caudal temporal area Tpt (which is associated with auditory-spatial processing) and the dorsal frontal areas (that is associated with oculomotor and attentional control). Due to the lack of a direct dorsal connection of Broca’s homologue with the temporal lobe, but rather with the parietal lobe, Aboitiz and García (Aboitiz and García, 1997) proposed the parietal lobe to play a fundamental element in language evolution, linking indirectly the two key structures (Broca’s and Wernicke’s) by means of the SLF II and III. In their view, “it permitted the development of an interphase between the auditory processing device and a working memory circuit for complex vocalisations that includes infraparietal and ventral premotor regions”. Other theoretical accounts suggested that the absence or reduced degree of the AF’s terminations in the inferior frontal cortex (area 44) in NHPs led to the lack of syntax (Friederici, 2017) or action-perception representations (Pulvermüller, 2018) that are necessary for language.

A conceptual change in the views of the AF’s frontal terminations happened when the cytoarchitectonical equivalence of Broca’s area 44 was established in the macaque (Petrides et al., 2005), which prompted a series of tract-tracing experiments to reinvestigate the frontal-parietal-temporal pathways with new and more precise tracer injection sites (Petrides, 2014) (Fig. 5). Following a detailed comparative analysis of the cytoarchitecture of macaque and human frontal cortex, Petrides and Pandya (Petrides, 2005; Petrides et al., 2005; Petrides and Pandya, 1999, 2002) established critical correspondences between the various frontal areas between the two species. In particular,
this work revealed for the first time the precise organisation of the homologues of Broca’s area 44 and 45 in the macaque brain. With these knowledge, the longitudinal fibre connections between the frontal, parietal and temporal lobe were re-investigated, leading to the major discovery of the existence of long arching fibres that directly connect macaque areas 44 and 45 to the caudal temporal cortex (Frey et al., 2014; Petrides and Pandya, 2009). Petrides explains in his 2014 book, that no terminations to area 44 and 45 were previously found, because the initial injection site was not placed ventrally enough within the temporal lobe (Petrides, 2014; Petrides and Pandya, 2009) (see Fig. 5 right panel that shows each different injection site with an arrowhead and the resulting course with a different colour).

In fact, this work revealed three AF branches projecting to the frontal cortex (see Petrides, 2014, pp 160, Fig 52): 1) A dorsal branch that connects from the dorsal part of the superior temporal gyrus to dorsal frontal area 8Ad and area 6; 2) A second branch that connects from the ventral part of the superior temporal gyrus, and the upper bank of the superior temporal sulcus to area 44; and 3) A last branch that connects from the caudal superior temporal gyrus and the adjacent bank of the superior temporal sulcus to area 45 (Fig. 3). This result was recently reproduced in comparative dMRI studies, in-vivo and ex-vivo, in macaques and chimpanzees (Baleazeau et al., 2020; Barrett et al., 2020; Bryant et al., 2020; Eichert et al., 2019, 2020; Rilling et al., 2008; Roumazelles et al., 2020) and on a functional level using effective connectivity (Ricchi et al., 2021).

As such, the recent tract-tracing data, it is clear that AF connections to the inferior frontal cortex exist in the macaque brain, as in humans, suggesting that the so-called human language pathway between Broca’s and Wernicke’s areas might be more preserved in nonhuman primates than previously thought. Further supporting this conserved primate AF-inferior frontal cortical connectivity, recent studies have also reported common roles of macaque and humans frontal areas 44 and 45 in cognitive vocal control (Loh et al., 2017, 2020). As such, contemporary theories that explain the uniqueness of human language based on the absence of inferior frontal projections of the AF must be revised accordingly. If AF frontal terminations are highly conserved, the question arises why language has evolved in humans alone? This important open question remains to be addressed by future research.

3.2. Question 2: Do human AF terminations extend further into the temporal lobe than in nonhuman primates?

In the human brain, the AF arches around the Sylvian fissure, and extends beyond the posterior part of the superior temporal gyrus, where the Planum Temporale and Tpt lies, and stretches into the middle temporal gyrus (e.g., Rilling et al., 2008; Catani et al., 2005; see Fig. 3 left panel), and anterior temporal areas (e.g., Eichert et al., 2019). This middle part of the temporal cortex is associated with semantic verbal (or multimodal) information (Binder et al., 2009), and as such, this implies that the human AF provides the frontal language areas access to semantic information in the middle temporal gyrus. The difference in temporal terminations between human and NHP is therefore crucial, in order to investigate potential evolutionary divergences, which, in turn, influence functional theories about language evolution. It is, however, not to be excluded that this human-unique feature could be: 1) due to the expansion of the temporal lobe alone (Eichert et al., 2019; Van Essen and Dierker, 2007); or 2) due to methodological differences (Latini et al., 2021; Petrides, 2014) (Fig. 4).

In their diffusion MRI work, Rilling and colleagues (Rilling et al., 2008, 2012) described major changes during primate evolution with an increased temporal lobe projection in the human brain and related this finding to language evolution. While the human AF reaches the MTG, the macaque AF terminates at the caudal end of temporal area 22, near the temporo-parietal junction. As such, Rilling et al. (2008) suggested that the human AF is unique in its extended projections into the middle temporal gyrus. This finding has become the basis of a number of models of human language processing. For example, in their model for “Social Communication And Language Evolution and Development” (SCALED), Catani and Bambini (2014) linked the lack of the AF’s deep terminations into the middle temporal gyrus and anterior temporal areas (long temporal tail) in NHPs to the absence of syntax processing and reduced semantics processing.

At the same time as Rilling et al. (2008); Van Essen and Dierker. (2007) also proposed a theory of primate brain evolution that described a cortical expansion across primates using certain key regions of interest as common landmarks. They proposed that if the macaque brain was inflated to the size of a human brain, some areas would be too small in comparison to their human counterparts. Thus, these areas, including the middle temporal cortex, must have expanded disproportionally in size during evolution to match the actual human brain organisation. As such, this temporal cortical surface expansion could explain the apparent expansion of AF terminations into the middle part of the temporal lobe in the human brain.

By examining the surface projections of the temporal association tracts across primate species, a series of studies from Rogier Mars’ laboratory tackled the question of whether the observed extension of the AF’s termination into the human temporal lobe was due to cortical expansion alone, or also to an actual extension of the tract into new cortical regions (Bryant et al., 2020; Eichert et al., 2019, 2020; Mars et al., 2021; Roumazelles et al., 2020; Warrington et al., 2020). Eichert et al. (2019) first extracted the main body of the AF tract in both the macaque and human brain using common tractography protocols (Warrington et al., 2020). The cortical surface projections from these AF tract bodies were then computed in each species. Next, similar to Van Essen and Dierker. (2007), interspecies cortical surface transformations were computed using species-common cortical landmarks. Finally, by applying these cross-species surface transformations on the macaque AF tract projection maps and comparing them to the actual human AF maps, they examined whether cortical surface expansion alone would predict the apparent expansion of AF tract projections from macaque to humans (see also Eichert et al. (2020) for a similar method based on T1w/T2w maps alignments). This way, they demonstrated that cortical surface expansion alone cannot account for the expansion of the AF’s tract projections in the human temporal lobe (Eichert et al., 2019, 2020). The authors therefore conclude that the human AF underwent additional changes in its course by invading new middle and anterior temporal areas. Providing a full picture of how the AF and temporal...
cortex had evolved across primates, the same group of researchers proposed that the middle temporal region first underwent a significant cortical expansion in the great apes lineage, and subsequently, in human evolution, the AF extends into these new temporal territories, resulting in the expanded cognitive/language abilities in humans (Bouma et al., 2020).

Echoing these findings, Barrett et al. (2020) found no terminations exceeding the Tpt area to connect with frontal areas in macaque ex-vivo dMRI data, which were present in humans. They state that the AF shows the most striking differences among the various association tracts between humans and monkeys, with monkeys sharing only a small sub-component of the AF (roughly the body of the tract) with humans. As such, consensus lies in the fact that the monkey’s AF’s temporal tail terminates in the Tpt/Planum Temporale area (e.g., Schmahmann and Pandya., 2006), but see also (Schmahmann et al., 2007). This morphology is incomparable with that of the human, where it exceeds the middle temporal gyrus and anterior temporal areas.

However, very recent studies found for the first time connections between the functionally defined auditory cortex, and Broca’s homologue (Areas 44, 45). This result highlights a slightly more anterior temporal projection of the AF than previously found, since the auditory cortex is located in the middle and posterior superior temporal lobe, anterior to the Tpt/Planum Temporale area (where the AF has been shown to terminate in previous works). Based on this direct connection between the auditory cortex and Broca’s homologue, the authors speculate “that this dorsal auditory pathway is involved in not just spatial processing in the classical sense but also sound and vocal patterning in the time domain”, a function that had previously been exclusively limited to the Ventral Pathway (see Question 3). Note that in this description, the human AF also terminates in the posterior superior temporal lobe and does not exceed into the middle- or anterior parts of the temporal lobe.

However, the consensus that the human AF arches into the middle, anterior, and inferior parts of the temporal lobe is questioned by some authors (Latin et al., 2021; Maldonado et al., 2013; Petrides, 2014; Wang et al., 2013). In fact, in the monkey brain tract tracer studies have demonstrated that monosynaptic AF connections terminate around the Tpt/Planum Temporale area. Fibres arching further ventrally in the temporal lobe (i.e., temporo-parietal fibres like the posterior middle longitudinal fasciculus (MdLF), see Part I “Late 20th Century: Neural tract-tracing...”) are independent and build synapses with the AF (Diestler et al., 1993; Petrides, 2014; Seltzer and Pandya, 1984). The possibility cannot be excluded, that this morphology may be similar in the human brain, with the human AF also originating in area Tpt/Planum Temporale if defined monosynaptically. However, with diffusion MRI, one is unable to distinguish between a monosynaptical AF terminating in area Tpt/Planum Temporale or a polysynaptical AF intermingled with tracts running through the temporal lobe, like the posterior MdLF (as proposed by Latin et al., 2021; Maldonado et al., 2013; Petrides, 2014; Wang et al., 2013). In other words, in this view, the human AF might be losing its predominant “arch” (which might correspond to the posterior indirect segment (Catani et al., 2005) due to methodological issues (Fig. 3). It is possible that this hypothesis influenced the most recent comparative investigations (Balezeau et al., 2020; Rocchi et al., 2021).

If we consider the hypothesis that the temporal projections of the human AF indeed terminate at the posterior superior temporal cortex as in the macaque (e.g. Latin et al., 2021; Maldonado et al., 2013; Petrides, 2014; Wang et al., 2013), what, then, might be the cause of the apparent differences in temporal lobe tractography between humans and monkeys? One possibility could be that, besides the AF, the various tracts that run through the temporal lobe (e.g., the Inferior Longitudinal Fasciculus (ILF) Inferior Fronto-Occipital fasciculus (IFOF), the Middle Longitudinal Fasciculus (MdLF), Uncinate Fasciculus (UF), Extreme Capsule Fasciculus (EFC) etc.) might have expanded along with human temporal lobe evolution (Braunsdorf et al., 2021). These tracts are considered part of the Ventral pathway and might be interconnected with the AF (Braunsdorf et al., 2021; but see Billing et al., 2012, for the exclusion of potential ILF contamination during the reconstruction of the AF). In other words, this idea is in line with a human-specific evolution of temporal lobe connectivity that is not, however, due to the AF, but to other tracts.

In summary, current consensus lies in the divergence of AF temporal terminations. Monkeys possess terminations in the most posterior part of the temporal lobe, even though recent advances pushed these terminations more anteriorly into the auditory cortex (Balezeau et al., 2020). In humans, the AF extends into the middle part of the temporal cortex, and for some authors more anterior-inferiorly into anterior temporal areas. Even though the possibility has to be highlighted that this extension, relative to macaques, might be due to polysynaptic connections with other Ventral Pathway fasciculi such as the posterior part of the MdLF. In the future, investigations have to show whether this difference in temporal terminations between human and NHP is genuinely crucial and accounts for the evolution of language in the human lineage.
3.3. Question 3: has the Dorsal Pathway, relative to the Ventral Pathway, expanded significantly in humans?

Recent language models depict a Dual Pathway model (Hickok and Poeppel., 2004) which emulates the well-known visual system division into a Ventral and a Dorsal Pathway. In this model, both pathways connect the inferior frontal to the temporal lobe, with the Dorsal Pathway curving dorsally around the Sylvian fissure, and Ventral Pathway passing ventral to the Sylvian fissure. Traditionally, at the functional level, the Dorsal Pathway is involved in mapping sound to articulation, while the Ventral Pathway is involved in mapping sound to meaning (Hickok and Poeppel., 2004; Saur et al., 2008). There has been great interest recently in understanding how these pathways have differentially evolved across species due to their direct relevance to human language functions. Due to limitations in disentangling fibre bundles in dMRI tractography, it is anatomically unclear exactly which fibre bundles form these two broad conceptual pathways. While it is generally accepted that the AF together with SLF II and III make up the Dorsal language Pathway (see part I), the exact tracts that constitute the Ventral Pathway remain ill-defined in the literature. As such, many diffusion MRI studies thus cannot account for a clear separation of the individual tracts constituting the Dorsal and Ventral Pathways and have therefore instead based their interpretations on this broad Dorsal/Ventral dichotomy (e.g., Balezeau et al., 2020; Eichert et al., 2019; Rilling et al., 2008, 2012). For this reason, we also keep here the appellation “Dorsal and Ventral Pathways” as in the original articles (e.g., Rilling et al., 2008, 2012). While both pathways connect similar areas, it is the Dorsal Pathway that is dominant in humans (i.e., stronger structural connectivity than the Ventral Pathway) (Rilling et al., 2008). A crucial question is therefore whether the same organisation is shared with monkeys.

Currently, there are several theoretical accounts based on how a reduced Dorsal- versus Ventral dominance in nonhuman primates could explain the uniqueness of human language (e.g., Friederici, 2017; Pulvermüller, 2018; Rilling et al., 2008, 2012). However, with differences in seedling and the addition of functional connectivity, recent investigations have challenged this view and show increased connectivity on the structural side for the Dorsal Pathway and an equal dominance of both pathways on the functional side in monkeys (Balezeau et al., 2020; Rocchi et al., 2021). Here, we review tractography and effective connectivity studies of the Dorsal and Ventral Pathways to investigate whether or not a stronger ventral-than-dorsal ratio exists in the nonhuman primate’s brain.

In their pioneering work, Rilling and colleagues (Rilling et al., 2008) compared the Dorsal and Ventral Pathway across primate species, using dMRI and a probabilistic multi-fibre diffusion model. They found a stronger (more streamlines) Dorsal-than Ventral Pathway in human, which was not the case in macaques and chimpanzees. In fact, for macaques a very weak (i.e., low number of streamlines) Dorsal Pathway that is dominant in humans (i.e., stronger structural connectivity than the Ventral Pathway) (Rilling et al., 2008). A crucial question is whether or not a stronger ventral-than-dorsal ratio exists in the nonhuman primate’s brain.

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A first prominent theory comes from Angela Friederici as highlighted in her 2017 book “Language in the brain” (Friederici, 2017). She proposes that complex syntax and therefore human language developed in human only, due to the strengthening of the Dorsal Pathway with extension of terminations into area 44 (part of Broca’s area). The reasoning is the following: The Dorsal Pathway conveys complex syntax in the human brain due to the connection to area 44 (Friederici et al., 2006), whereas the Ventral Pathway conveys semantic aspects of language and simple syntax due to the connection to area 45 and the frontal operculum (Friederici, 2017). Monkeys however show none or only weak dorsal connections to area 44 (Rilling et al., 2008), but have ventral termination to this area. Therefore, they don’t show complex syntax, but aspects of semantics and simple syntax (Friederici, 2017). Indeed, behavioural data indicates that monkeys fail to show the processing of complex syntax, but showed aspects of semantics (Friederici, 2017). In addition, behavioural data in developmental studies highlight that infants only acquire complex syntax by the age of seven, exactly when the most anterior portion of the Dorsal Pathway matures and connects to Broca’s area (Brauer et al., 2013, 2011; Friederici, 2017; Perani et al., 2011). In contrast, the Ventral Pathway connection into this area is already present at that age (Brauer et al., 2013, 2011; Friederici, 2017; Perani et al., 2011).

Fig. 6. Dorsal- versus Ventral Pathway strength (question 3). (Left) A dominance in strength (in structure and function) in the Ventral Pathway (green) against the Dorsal Pathway (red) (e.g., Rilling et al., 2006, 2012). (Right) Equal strength (in function) between both pathways (e.g., Rocchi et al., 2021).
However, there are also some limitations to this theory:

First, several dMRI studies interpret the developmental data differently (Dbois et al., 2005, 2016). In their view, Dorsal Pathways’ terminations to Broca’s area are present before the age of 7, but intractable in dMRI due to their immature microstructure. Second, more recent behavioural studies highlight that monkey can “break to the syntax barrier” (Ferrigino et al., 2020; Jiang et al., 2018; Malassis et al., 2020; Finch, 2018). A second recent and influential theory based on a weaker Dorsal Pathway (AF) is post by Pulvermüller (Pulvermüller, 2018). He hypothesised that the overall strengthening, and the evolutionary new and stronger area 44 termination of the Dorsal Pathway enabled frontotemporal sensorimotor shortcuts, connecting further than just next neighbouring areas. This way, humans can better bind action and perception into circuits that support cognitive functions important for language processing, like working memory, prediction, attention, and combination, including abstract rule formation. In this work, action representations lie at the heart of language processing. Very recently however, changes in techniques and seeds for tracking have provided the first arguments against the view of a stronger-Ventral-than-Dorsal-Pathway in monkeys. In a diffusion MRI studies across primate species, Balezeau and colleagues (2020) used a functionally defined auditory cortex as the seed for tractography. This way, they highlighted a Dorsal Pathway connection into the auditory cortex, which was until then reserved to the Ventral Pathway (Rilling et al., 2008; Romanski et al., 1999). The authors therefore suggest that the monkey AF is not solely involved in low-level processes but instead important for sound and vocal patterning in the time domain (Balezeau et al., 2020). Furthermore, on the functional level, using functional MRI while electrically stimulating the same auditory cortex (termed “effectivity connectivity”), Rocchi and colleagues (Rocchi et al., 2021) reported that Dorsal and Ventral Pathways connect to the same degree to Broca’s area (Brodmann area 44) and to the primary motor cortex (Brodmann area 4). However, Dorsal AF was shown stronger on a structural level (Rilling et al., 2008, 2012), functionally both pathways have the same strength. The authors suggest therefore that language abilities allowing humans to name, conceptualize and thus better remember sound (Schulze et al., 2012) would be shared across primates (Fig. 6 right panel). Based on the above recent data, the long-standing bulwark of a reduced Dorsal Pathway dominance that could explain language evolution is beginning to crumble. As a result, contemporary theories that explain the uniqueness of human language based on the proportional strength of the Dorsal and Ventral Pathway, might benefit from a revision. While structural differences in strength may persist between the human and the monkey Dorsal Pathway, this may not be the case functionally. A question that exceeds the current review is to investigate whether structural differences are therefore of importance on other functional levels as investigated by Rocchi et al. (2021).

3.4. Question 4: A continuous evolution of the AF across primates - could AF lateralisation be the key to human language?

In humans, the AF is strongly lateralised towards the left hemisphere (Thiébaut de Schotten et al., 2011b). This structural lateralisation is of interest, because the majority of the language system is also functionally left-lateralised in the brain (e.g., Toga and Thompson, 2003). Whether such a same lateralisation exists, or not in nonhuman primates is therefore a crucial question that would shed light on the origins of human language lateralisation. Especially, since the most recent investigations about the AF’s anatomy across primates agree on a highly evolutionarily conserved anatomy (see sections above). Thus, the question about anatomical differences across primates, that might explain the human uniqueness for language, persists. Authors of recent investigations highlight that the left AF lateralisation is the crux of the human-specific distinction (Balezeau et al., 2020; Eichert et al., 2019; Rocchi et al., 2021). While carefully reviewing the recent comparative brain lateralisation data, we conclude that this compelling idea lacks sufficient sample size.

From early human development on, inter-hemispheric asymmetry was documented for most language-related regions at both structural and functional level. In fact, language tasks elicit greater activation in the left- than in the right hemisphere, even in newborns (e.g., Dehaene-Lambertz et al., 2002). Structural markers of such language brain lateralisation were proposed, like the leftward lateralisation of the Planum Temporale, Broca’s area or the Insula (e.g., Geschwind and Levitsky, 1968; Keller et al., 2013; Pulvermüller, 2018). He hypothesised that the overall strengthening, and the evolutionary new and stronger area 44 termination of the Dorsal Pathway enabled frontotemporal sensorimotor shortcuts, connecting further than just next neighbouring areas. This way, humans can better bind action and perception into circuits that support cognitive functions important for language processing, like working memory, prediction, attention, and combination, including abstract rule formation. In this work, action representations lie at the heart of language processing. Very recently however, changes in techniques and seeds for tracking have provided the first arguments against the view of a stronger-Ventral-than-Dorsal-Pathway in monkeys. In a diffusion MRI studies across primate species, Balezeau and colleagues (2020) used a functionally defined auditory cortex as the seed for tractography. This way, they highlighted a Dorsal Pathway connection into the auditory cortex, which was until then reserved to the Ventral Pathway (Rilling et al., 2008; Romanski et al., 1999). The authors therefore suggest that the monkey AF is not solely involved in low-level processes but instead important for sound and vocal patterning in the time domain (Balezeau et al., 2020). Furthermore, on the functional level, using functional MRI while electrically stimulating the same auditory cortex (termed “effectivity connectivity”), Rocchi and colleagues (Rocchi et al., 2021) reported that Dorsal and Ventral Pathways connect to the same degree to Broca’s area (Brodmann area 44) and to the primary motor cortex (Brodmann area 4). However, Dorsal AF was shown stronger on a structural level (Rilling et al., 2008, 2012), functionally both pathways have the same strength. The authors suggest therefore that language abilities allowing humans to name, conceptualize and thus better remember sound (Schulze et al., 2012) would be shared across primates (Fig. 6 right panel). Based on the above recent data, the long-standing bulwark of a reduced Dorsal Pathway dominance that could explain language evolution is beginning to crumble. As a result, contemporary theories that explain the uniqueness of human language based on the proportional strength of the Dorsal and Ventral Pathway, might benefit from a revision. While structural differences in strength may persist between the human and the monkey Dorsal Pathway, this may not be the case functionally. A question that exceeds the current review is to investigate whether structural differences are therefore of importance on other functional levels as investigated by Rocchi et al. (2021).

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unclear why cerebral asymmetries are commonly detected in baboons but not in macaques. Based on the above tractography data, the question about evolutionary continuities or discontinuities in AF lateralisation will need further investigations with 1) ample sample sizes also in regard to handedness and 2) the inclusion of the baboon as a representative of the Old world monkey family. Therefore, we predict that future studies will focus on this crucial question in language brain evolution.

4. Discussion and conclusion

The apparent literature about the evolution of the AF has been rapidly gaining in interest in very recent years and is used as a base for theories about language evolution. However, no clear consensus was found, due to differences in apppellations and divergent anatomical courses and terminations, which are resulting in diverging definitions of what exactly the AF is. For example, anatomically, AF and SLF generally refer to the same tract. This is important as the label “AF” implies “language pathway” more than the labels SLF, MdLF or Dorsal Pathway. But note that all terms are used interchangeably throughout the literature. However, differences in terminology matters, because a same result could have different theoretical implications depending on its labelling and therefore its functional connotation. To illustrate this point we can do a thought experiment: If, during primate evolution, an increase of connectivity strength between the superior temporal lobe (Wernicke’s area) and the inferior parietal lobe (Geschwind’s region) (as in e.g., Aboitiz and Garcia, 1997; Catani and B Break, 2014) was documented, different functional interpretations could be drawn from this, depending on terminology. We could label this segment for example AF, SLF, MdLF or Dorsal Pathway. However, the functional implication would be most associated with language evolution for the label “AF”, even though the segment is the same.

In this review, we have therefore carefully highlighted the history of AF anatomy across primate species and defined a clear current anatomical model. The AF/SLF complex can be divided into four distinct fibre bundles including: 1) the AF, which comprise in itself three fibre branches that arch dorsally around the Sylvian fissure and connect the posterior temporal cortex (area Tpt, posterior auditory cortex) with the frontal cortex (area 44, 45, area BA6 and 6) and 2) the SLF, II and III which comprise the three longitudinal fibre bundles that interconnect distinct parts of the frontal and parietal cortex and are not arching around the Sylvian fissure. In addition, we focused on four discontinuous key changes in AF anatomy that are discussed to differentiate the human from the nonhuman primate. These are grouped in research questions concerning: frontal terminations (1), temporal terminations (2), the proportion of the Dorsal- versus Ventral Pathway strength (3) and lateralisation (4). These four key questions are of high importance, because their results in terms of (dis)continuity influence theories about language evolution. Based on the latest results of these four key questions, we argue that the evolution of the AF anatomy is more continuous across primate species than previously described. When summarizing the four questions (see also Table 1), we can notice the importance of methodological changes that are pivotal in the conceptualisation of the AF anatomy:

- Historically, knowledge about the AF’s terminations (Question 1) relies strongly on invasive tract tracing studies in the monkey brain. Findings about differences in frontal termination in the macaque brain (no Broca’s terminations) compared to the human brain (Broca’s termination) led to theories about the specific frontal development of the human AF, important for language processing. However, human-like terminations into Broca’s homologue in monkeys were found when cytoarchitectonic equivalence was demonstrated and tract tracing injection sites changed. Therefore, the frontal termination’s organisation seems to be conserved during primate evolution, even though terminations might have become overall stronger in humans.

- The same applies to the temporal terminations (Question 2), which were initially found to be very extended in humans, exceeding the middle part of the temporal lobe into its anterior and inferior parts. New data from methodological changes indicate however, that first, the monkey’s terminations are also slightly more extended (tracking from the functionally characterised auditory cortex) and second, the

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human extension could be a technical artefact (possible entanglement with fibres running through the temporal lobe like the MdLF). Therefore, it is not excluded that the terminal organisation’s nomination might also be more conserved during primate evolution, even though the temporal connections might have become overall stronger in humans.

- Finally, pivotal changes in the question of the proportion of the Ventral- versus the Dorsal Pathway’s strength (Question 3), can also be illustrated by changes in the connectivity (effective connectivity) and seed masks (tracking from the functionally characterised auditory cortex). Initially found to be very weak and not terminating into the auditory cortex, the Dorsal Pathway in monkeys might now be regarded as functionally as strong as the Ventral Pathway and also connecting with the auditory cortex. Therefore, the possibility is not excluded that the Ventral-versus-Dorsal Pathway strength organisation might be conserved during primate evolution, even though it is possible that the Dorsal Pathway might have become overall structurally stronger in humans.

- Using this method-based framework on the question of lateralisation (Question 4), we can say that currently only the progress of tractography methods and dMRI acquisition techniques could advance this question as tract-tracing methods are not adapted. In particular, a forthcoming development of tractography applied to a large-scale cohort of non-human primate data could further advance the question as it was already conducted in chimpanzees concerning the lateralisation of other tracts like the SLF (Hecht et al., 2015), or structural grey matter asymmetries (e.g., Hopkins et al., 2015). Therefore, the question of AF lateralisation across primates needs a specific attention in the future. Given existing results about the left-lateralisations of persimilvian regions in monkeys (Becker et al., 2021a, b, Becker and Meguerditchian, 2021; Marie et al., 2018), it is not excluded that a human-like left lateralisation could also be demonstrated in monkeys in the future, even though lateralisation might have become stronger in human evolution.

Last but not least, we do not want to understate the importance of comparative AF studies for the investigation of language brain evolution. In fact, the reviewed data points towards a progressive evolution of the AF during primate evolution, rather than great leaps that would indicate categorical changes of the AF’s morphology between contemporary primate species. This progressive evolution could be expressed by a progressive 1) strengthening of connectivity, 2) expansion of terminations and 3) lateralisation of features that have already present in the common ancestor of Old world monkeys, chimpanzees and humans. However, future studies must also focus on other tracts that have undergone substantial changes during primate evolution and that are linked to language processing in humans. Possible tracts of interest are tracts that run through the temporal lobe (and might be constituents of the Ventral Pathway, depending on its definition), like the Inferior Longitudinal Fasciculus (ILF), Inferior Fronto-Occipital fasciculus (IFOF), the Middle Longitudinal Fasciculus (MLF), Uncinate Fasciculus (UF), Extreme Capsule Fasciculus (ECF). But also, the Frontal Aslant, which connects the supplementary motor areas, the lateral superior frontal gyrus and the cingulate cortex to the inferior frontal gyrus could be a candidate to focus on (for a review: La Corre et al., 2021). In conclusion, recent works in humans and nonhuman primates suggest that the AF course and terminations are more similar between species than described before. The remarkable human ability of language might therefore have evolved progressively in primate evolution, exactly as its underlying anatomic implementation in the brain. Or to put it in the words of Charles Darwin: ‘‘Nevertheless the difference in mind between man and the higher animals, great as it is, certainly is one of degree and not of kind.’’ (page 105: Darwin, 1871/1981).

Future theories about language brain evolution should account for this continuous, and not discrete AF evolution.

Data availability
No data was used for the research described in the article. All data is within the manuscript and figure.

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8. Discussion

This thesis is part of the research on the origins of language through a comparative approach between primate species. In particular, this work focused on the peculiar organisation of the human language network in the brain: its structural lateralisation in the left hemisphere. Therefore, the thesis investigated the ontogenic and phylogenetic origins of such organisation in newborn and adult moneys. The research articles at the heart of this present dissertation are focused on advancing, in particular, three critical questions about the evolution and development of the perisylvian lateralisation:

1. Is a lateralised perisylvian organisation shared beyond humans and apes, but with Old world monkeys?
2. When does such an asymmetric organisation appear in nonhuman primate development and does it predict later behaviour?
3. If such structural brain lateralisation is shared with our non-linguistic primate cousins, for what behavioural functions did it evolve, if not for language?

These questions are crucial for investigation the evolution of language and its underlying brain hemispheric organisation. Indeed, in response to the current debate about a continuous or discontinuous language evolution, the thesis examined whether the lateralisation of perisylvian brain structures is shared between species. It will next investigate whether such an organisation is unique to human infants, or if such early lateralisation also exists in nonhuman primate infants. In addition, the thesis also examines whether early cerebral development shapes later behaviour, or vice versa. Finally, one crucial question comes to mind: If this lateralised perisylvian organisation is indeed shared between primate species, for what behaviour or cognitive function did it initially evolve? In other words, what might be the precursors of the brain organisation that supports language in the human species?

These questions were treated altogether or once a time in my research articles. For example, study 1 and 2 treated the first two questions, while study 3 treated all the three questions together. In the following, I will discuss these questions in the lights of our results.
8.1. Is a laterised perisylvian organisation shared beyond humans and apes, but with Old world monkeys?

In line with results in adult baboons (Marie et al., 2018), we were able to demonstrate that newborn baboons showed both individual and population-level leftward surface (study 1) and grey matter volume (study 2) asymmetries of the Planum Temporale. These results showed intraindividual positive correlation of Planum Temporale surface and grey matter measures on the same subjects as well as consistent leftward Planum Temporale asymmetry (Becker et al., 2021a;b). This suggests that Planum Temporale surface measures may therefore reflect its underlying grey matter volume. Interestingly, no sex or brain size effects were found on direction or strength of Planum Temporale surface and grey matter volume asymmetry. This finding contrasts brain size effect findings in adult baboons (Marie et al., 2018) and the hypothesis of Planum Temporale asymmetry increase due to increase of brain volume in Hominidae evolution (Pilcher et al., 2001). The distributions of individual Planum Temporale hemispheric preferences (left, right or ambi) are quite similar between volumetric
Figure 8.2. – (A) Representation of the asymmetric Planum Temporale (PT) in the baboon brain on a T2w image according to a coronal section, 3D brain render and oblique section oriented along the Sylvian Fissure (the left PT is in red and the right PT in green). (B) Mean Asymmetry quotient (AQ) for the Planum Temporale surface of the newborn infant baboons (N = 35). Negative Mean AQ score indicates leftward hemispheric asymmetry at a population-level. The long black line represents the median, the white short line the mean. p < 0.0001 (C) Subjects distribution (in percentage) as a function of the direction of their PT asymmetry in baboon infants (N = 35, in red) versus in human infants (N = 100, in blue, from Wada, 1975). (D) Variation of strength of the Planum Temporale surface’s asymmetry (Mean absolute AQ score) among the 29 baboons scanned longitudinally at two early stages of development: Newborn (in red) versus Juveniles (i.e., from 7 to 10 months in blue). p < 0.05.

grey matter and surface measures, especially for the left laterised subjects, although some inconsistency was noticed at the individual-level in a minority of subjects. It remains unclear whether those variations are due to interrater-dependent variability in the measures, which leads few subjects to switch categories, or to the possibility
that Planum Temporale surface measures are not entirely perfect “tip of the iceberg” predictors of the Planum Temporale grey matter volume, especially for the subjects initially classified as ambiguously biased for Planum Temporale surface. In fact, almost all of those latter “ambi” newborns (six out of seven) were found to be significantly lateralised for Planum Temporale grey volume. In addition, Asymmetry Quotient values were overall higher in grey matter measures (AQ $-0.121$, 12.1 %) compared to surface measures (Asymmetry Quotient $-0.073$, 7.3 %). A similar effect was found in Hopkins and Nir's paper (2010) in chimpanzee, which showed a 4.96 % larger left hemisphere when measuring its surface and 6.63 % larger hemisphere when measuring its grey matter. Therefore, measures of grey matter volume may be more likely to capture interindividual differences of the Planum Temporale asymmetry, whereas the surface measures may only scratch the top of the Planum Temporale iceberg. Our findings are also somewhat consistent with averaged-brain leftward asymmetries found in infant Rhesus macaques within large temporal clusters which seem to overlap with Planum Temporale according to an automated source-based method (Xia et al., 2019).

Figure 8.3. – (A) Distribution of asymmetry quotients (AQ) for grey matter (GM) volume measures in red and surface area measures in blue for the same subjects. AQ values inferior to zero indicate leftward lateralisation, AQ values superior to zero indicate rightward lateralisation. Note the leftward lateralisation for both measure types. Note also larger distribution, i.e., higher AQ values for the grey matter volume measures.

Regarding Broca’s homologue in adult baboons (study 4), we have not demonstrated a clear population level structural asymmetry. This is in line with research in humans, in which a population-level leftward asymmetry of Broca’s area is debated (see Sprung-Much et al., 2021 for a recent review and the present part about Broca’s area in the Introduction). Nevertheless, we showed that the Inferior Arcuate sulcus’ left- or rightward depth asymmetry at its mid-ventral and ventral portion (labelled as the “Broca cluster”) is associated exclusively with contralateral direction (left-/right-hand).
of communicative manual gestures’ lateralisation in baboons. This demonstrates a structural asymmetry at the individual level, dependent on handedness for gestural communication, which might be shared between human and nonhuman primates (see more in Question 3).

The result highlights the importance of an individual-level approach, because studies are rare investigating the direct behavioral/brain correlates at the individual-levels to test potential phylogenetic continuity. When half of the subjects are lateralised towards one direction and the other half to the opposite direction, the average value would show an absence of lateralisation.

In fact, it must also be noted that not all humans are left lateralised for perisylvian structures neither. Indeed, structural left lateralisation of perisylvian regions like the Planum Temporale occur in about 65 % of the (human) population just like in nonhuman primates (e.g., Geschwind and Levitsky, 1968). In addition, difference in degree in the population-level leftward lateralisation between baboons and humans does not mean that there is no continuity in the underlying behavioural/brain correlates at the individual level. It is probable that a population-level bias, which is present in the baboon, has increased in humans in the course of the evolution.

Regarding the Arcuate Fasciculus that interconnects Broca’s area with the Planum Temporale, I focused in the review on four discontinuous key changes in Arcuate Fasciculus anatomy that are discussed to differentiate the human from the nonhuman primate. Frontal terminations, temporal terminations, the proportion of the Dorsal-versus Ventral Pathway strength and lateralisation. These four key morphological features are of high importance, because their results in (dis)continuity influence theories about language evolution. When summarising results about the four features, we can notice the importance of methodological changes that are pivotal in the conceptualisation of the Arcuate Fasciculus anatomy: Human-like terminations into Broca’s homologue in monkeys were found when cytoarchitectonic equivalence was demonstrated and tract tracing injection sites changed. Therefore, the frontal termination’s organisation seems to be conserved during primate evolution, even though terminations might have become overall stronger in humans.

New data from methodological changes indicate that temporal terminations in monkeys are slightly more extended (tracking from the functionally characterised auditory cortex) and second, that the human extension could be a technical artefact (possible entanglement with fibres running through the temporal lobe like the MdLF). Therefore, it is not excluded that the temporal termination’s organisation might also be more conserved during primate evolution, even though the temporal connections might have become overall stronger in humans.

The Dorsal Pathway in monkeys might now be regarded as functionally as strong as the Ventral Pathway and also connecting with the auditory cortex. Therefore, the possibility is not excluded that the Ventral-versus-Dorsal Pathway strength organisation might be conserved during primate evolution, even though it is possible that the Dorsal Pathway might have become overall structurally stronger in humans.

In order to highlight anatomical differences across primates, which could explain the human uniqueness for language, several authors conclude that the left Arcuate Fas-
ciculus lateralisation is the crux of the human-specific distinction (Eichert et al., 2019; Balezeau et al., 2020; Rocchi et al., 2021). In fact, Rilling et al. (2008) did not find any AF asymmetry in three macaque and four chimpanzee subjects. However, by adding more chimpanzee subjects, the authors were able to report a left lateralised AF which was still weaker than in humans (Rilling et al., 2012). This result remained unique regarding AF lateralisation in nonhuman primates (Eichert et al., 2019, Balezeau et al., 2020; Rocchi et al., 2021). In fact, this inconsistency in the literature on the presence or absence of a leftward AF bias at the population level could be explained by the small sample size (i.e., only a few subjects) usually included in these nonhuman primate AF studies, which makes it difficult to infer a bias at the population level. Only studies with a much greater sample of subjects would help to clarify this debate.

Based on latest results of these four morphological key features, the review argues that the evolution of the Arcuate Fasciculus anatomy is more continuous across primate species than previously described. Latest functional results suggest that language abilities allowing humans to name, conceptualize and thus better remember sound (Schulze et al., 2012) would be shared across primates (Rocchi et al., 2021).

Figure 8.4. – The three branches of the Arcuate Fasciculus (AF) (red) in the human brain (left) and in the monkey brain (right). Note the similar courses and cytoarchitectonical termination sides between the two species. See study 5/Becker et al., 2022b in this present thesis.

Based on the overall results, I hypothesise that asymmetries for language areas may not have initially evolved for language, if language is seen as one cognitive module. Rather, each asymmetry could have evolved independently for independent cognitive functions, to adapt to potential environmental pressures. This could explain the unclear relationship between structural and functional asymmetries related to language areas (see the introduction of the present thesis). The structural asymmetry would here be a more ancient fossil of other cognitive specialisation on which the functional language asymmetry got piggybacked. The functional and structural specialisation of these structures may next have been important nests for developing intentional communicative behaviour in nonhuman primates, which later evolved to language processing in our species. In other words, “perisylvian language asymmetries” are not specific to language but could rather be exaptations of pre-existing specialisations for
other cognitive functions, which together make up what we call “language”. Therefore, “domain general” language-related brain architecture associated with intentional communicative or syntactic behaviours might rather be shared between humans, apes and at least baboons of the Old world monkey family.

8.2. When does such an asymmetric organisation appear in nonhuman primate development and does it predict later behaviour?

The results showed that early post-natal nonhuman primate infants present a significant human-like neuroanatomical asymmetry of the Planum Temporale surface in favour of the left hemisphere (see figure 8.2 above). This finding is clearly consistent with early Planum Temporale asymmetry found in human newborns and infants (Chi et al., 1977a;b; Dubois et al., 2010; Glasel et al., 2011; Hill et al., 2010; Wada, 1975; Witelson and Pallie, 1973) although measurement methods, Left-Right-Ambi classification threshold and statistical power in terms of sample size differ as well as age class equivalence, which overall make interspecies comparison challenging. Nevertheless, the distribution is quasi-identical to the ones reported in both human infants and human adults (Geschwind and Levitsky, 1968) but also in adult chimpanzees (Hopkins and Nir, 2010) and adult baboons (Marie et al., 2018). Such a similar age-related phenomenon was also described in human infants by Wada (1975). Interestingly, we found that the direction of individual Planum Temporale asymmetry is consistent across age classes while its strength is increasing with age. In fact, we found that the direction of individual Planum Temporale surface and volume asymmetry is not affected by age within this early age class. However, in Study 1, we found that the degree of Planum Temporale surface asymmetry was increasing latter in the development (i.e., at the upper age class: 7–10 month of age), suggesting that the strength of the Planum Temporale grey matter volume asymmetry should also increase at this upper age class (see figure 8.2). In addition, an absent sex effect in infant baboons, adult baboons (Marie et al., 2018) and human infants (Dubois et al., 2010) contrasts findings in human adults (Hirnstein et al. 2019).

These findings in a non-linguistic species clearly questions the historical idea that such a maturational effect of the Planum Temporale asymmetry’s strength is related to language development in human infants (Wada, 1975). One could ask whether the existence of the asymmetry shortly after birth has an innate, and thus, genetic component as hypothesized for human infants (Hill et al., 2010) or to what extent it is rather influenced by pre- and post-natal experience. In any case, the collective findings clearly provide additional support for the phylogenetic continuity between human and nonhuman primate species about such a brain asymmetric feature. Such a continuity extended at the earliest postnatal stage of development across both species may question the early Planum Temporale asymmetry as a human newborn-specific marker of the language-ready brain. Indeed, structural lateralisation of such a
language area may not solely account for a prewired brain for language acquisition as it was supposed for human babies (Dehaene-Lambertz et al., 2002).

Therefore, in study 3, we related gray matter Planum Temporale measurements from newborn baboons (study 2) (∼2 weeks old) to the manual behaviour of the same subjects once they reached their behavioural repertoire (>8 months of age, ∼2 years old). We demonstrated that direction of Planum Temporale grey matter asymmetry in newborn baboons predicts the development of later manual lateralisation for communicative gesture. Namely leftward brain biased newborns developed mostly right-hand preference for hand slapping gesture once juveniles, while rightward brain biased newborns developed no hand preference (see next section for the implication of gestural communication system as a potential candidate for an evolutionary shared cognitive process). In other words, the asymmetry of the Planum Temporale in newborn baboons, which exists before sophisticated motor development, is crucial for later development of lateralisation of complex intentional gestural communication. This result shows that, at least for the Planum Temporale, it is not the experience and later behaviour that reshape brain structure through brain plasticity (e.g., Kolb and Wishaw, 1998), but early in-womb experience and/or genetic coding that shape the newborn brain (e.g., Kolb and Gibb, 2011) and which in turn influence later behaviour. Therefore, exactly as in human infants, the Planum Temporale asymmetry has an innate/genetic “pre-wiring” (Hill et al., 2010) and accounts for later communicative behaviour, similarly as the “language-ready” brain (Dehaene-Lambertz et

Figure 8.5. – Distribution of Handedness Index (HI) for gestural communication at juvenile age for subjects that were classified as left biased (red) and right biased (green) for the Planum Temporale (PT) at birth. HI values inferior to zero indicate leftward lateralisation, HI values superior to zero indicate rightward lateralisation. Note the significant rightward handedness lateralisation for left biased PT (p < .05) and the significant difference between the two groups (p < .05). See study 3 in this present thesis.
al., 2002). Early Planum Temporale asymmetry might be thus not a human-specific marker for the prewired language-ready brain in infants. Nevertheless, it might be not excluded that this common anatomical signature is related to an ancient shared cognitive process between human language and monkey gestures at the heart of language evolution.

8.3. If such brain lateralisation is shared with our non-linguistic primate cousins, for what behavioural functions did it evolve, if not for language?

However, it remains unclear which factor is driving such a common early asymmetric feature of the brain anatomy among human and nonhuman infants. One potential explanation is that markers like the (early) Planum Temporale's, Broca's area's or Arcuate Fasciculus' structural asymmetry might have nothing to do with (the development of) functional language lateralisation, given some studies in adults reported no match between structural and functional asymmetry of these regions (Keller et al., 2011; Greve et al., 2013). Nevertheless, a recent study addressing this question in adults contradicts such a hypothesis (Tzourio-Mazoyer et al., 2018). Although the lack of match was confirmed between structural and functional asymmetry of the Planum Temporale in a language task, structural Planum Temporale asymmetry was found associated with functional lateralisation of an adjacent auditory area at the end of the Sylvian fissure, suggesting its links with language lateralisation. Therefore, another potential explanation is that the perisylvian structural asymmetry in both human and nonhuman infants might predict (the development of) homologous communicative functions, which still form a foundation for core aspects of the human language system. Determining such common developing functions between species remains highly speculative, given the lack of longitudinal studies in infants on the emergence of brain-behaviour relationships. Nevertheless, based on neuroimaging studies in adult nonhuman primate and on our present findings in newborn monkeys, it might be not excluded that shared properties of communicative systems in human and nonhuman primates could be related to Planum Temporale structural asymmetry. For instance, previous studies in monkeys and apes have reported human-like functional lateralisation for processing conspecific calls. However, its overlap with Planum Temporale anatomical region remains unclear as well as the direction of the functional lateralisation (i.e., toward left versus right hemisphere) which are inconsistent across the literature (e.g., Poremba et al.; 2004; Gil-da-Costa and Hauser 2006; Petkov et al. 2008; Joly et al., 2012). Alternatively, some authors have proposed that properties of the communicative gestural system in nonhuman primates could constitute another potential functional candidate of Planum Temporale specialisation. In fact, whereas production of communicative manual gestures have been found highly lateralised in favour of the right-hand in both baboons and chimpanzees (Meguerditchian et
al., 2013), a contralateral relation between Planum Temporale structural asymmetry and hand preferences for communicative gesture was reported in adult chimpanzees (Hopkins and Nir, 2010; Meguerditchian et al., 2012). These latter results have therefore suggested that the shared properties between gestural signalling in monkeys and the language system in humans may both be related to this asymmetric feature of temporal lobe anatomy (Meguerditchian et al., 2012).

Interestingly, in a previous study in chimpanzees, Hopkins and Nir (2010) noted that leftward Planum Temporale grey matter volume asymmetry constituted a better marker for lateralised behaviours than the Planum Temporale surface. In fact, the grey matter measurements predicted better the chimpanzee’s right-hand preference in communicative pointing gestures (but see also Meguerditchian et al. 2012). The latter study suggested the hypothesis that asymmetry in grey matter volume in the Planum Temporale may be associated with a functional asymmetry related to the properties of gestural communication in apes, which have been found to share common features with human language, such as intentionality, flexibility or referential properties (Liebal et al., 2013). Specifically, taking advantage of the stronger Planum Temporale asymmetries described in the present study for grey matter volume in comparison to surface measures, we could further investigate whether those early brain asymmetries might predict the gestural lateralisation’s emergence in later development. Therefore, in study 3, we related gray matter Planum Temporale measurements from newborn baboons (study 2) (~2 weeks old) to the manual behaviour of the same subjects once they reached their behavioural repertoire (~2 years old). We demonstrated that direction of Planum Temporale grey matter asymmetry in newborn baboons predicts the development of later manual lateralisation for communicative gesture. In other words, newborns with a larger left-than-right Planum Temporale developed more likely a right-handed communication once juvenile. No link was found with handedness for non-communicative actions.

We therefore propose the gestural communication system as a potential candidate for an evolutionary shared cognitive process, which is at the heart of communication. Indeed, this result demonstrate an evolutionary continuity between baboons, chimpanzee and humans, as in all three species a link between communication and cerebral asymmetry was found (Meguerditchian et al., 2012; Dehaene-Lambertz et al., 2002). In addition, we highlight a direction of causality between communicative behavior and underlying brain structures. Indeed, the Planum Temporale asymmetry is already present soon after birth and may shape the much later developing hand preference for gestural communication.

The results also indicate that the Planum Temporale didn’t evolved solely as a computational hub for complex sounds (Griffiths and Warren, 2002), but also seems to be specialised for other communicative functions related to intentional signals production such as gestures. In fact, an alternative view is that the Planum Temporale may be composed of functional subfields, with one performing motor processes (Hickok and Saberi, 2012). Indeed, recent results in implanted human patients showed that stimulation of the Planum Temporale selectively disrupts speech production (Forseth et al., 2020).
Similarly, regarding Broca’s homologue in adult baboons, we showed that the Inferior Arcuate sulcus’ left- or rightward depth asymmetry at its mid-ventral and ventral portion (labelled as the “Broca cluster”) is associated exclusively with contralateral direction (left-/right-hand) of communicative manual gestures’ lateralisation in baboons but not handedness for non-communicative actions (See study 4/Becker et al., 2022a). Building upon these first results, we also found a significant negative correlation between the Handedness Index values for gestures and the Asymmetric Quotient depth values of the Inferior Arcuate sulcus “Broca cluster”, suggesting that the contralateral links between handedness for gestural communication and depth asymmetries at the most ventral portion of the Inferior Arcuate sulcus is evident not only at a qualitative level but also at a quantitative level as well. In other words, individuals with a stronger degree of manual lateralisation for communicative gesture have greater Inferior Arcuate sulcus depth asymmetries at this ventral cluster in the hemisphere contralateral to their preferred hand for communication. The ventral positions of such sulcal depth asymmetries are clearly at a crossroad of Broca-related frontal regions including the fundus of the sulcus, Area 44 (Petrides et al., 2005, Petrides, 2005), the anterior bank, Area 45 (Petrides et al., 2005, Petrides, 2005), the posterior bank and ventral F5 or granual frontal area (GrF) (Belmalih et al., 2009; Rizzolati et al., 2019). Since the sulcus depth might reflect a gyral surface and its underlying grey matter volume, future work of delineating and quantifying grey matter of the ventral IA sulcus would help determining which of those sub-regions of the Broca homologue is driving the asymmetry specifically. Whereas handedness for manipulative actions in baboons was previously found related to the motor cortex asymmetry within the Central sulcus (Margiotoudi et al., 2019), our present findings report the first evidence in monkeys that the neurostructural lateralisation’s landmark of communicative gesture is located in a frontal region, related to Broca homologue. Such a contrast of results between manipulation and communication found at the cortical level is consistent with what was found at the behavioural level in studies showing that communicative gesture in baboons and chimpanzees elicited specific and independent patterns of manual lateralisation in comparison to non-communicative manipulative actions (Meguerditchian and Vaufclair, 2009; Meguerditchian et al., 2010). Therefore, it provides additional support to the hypothesis suggesting that gestural communication’s laterisation in nonhuman primates might be, just as language brain organisation in human (see Häberling et al., 2016), related to a different lateralised neural system than handedness for pure manipulative action. Its specific correlates with Broca homologue’s and Planum Temporale’s lateralisation is also consistent with what was found in our closest relatives, the chimpanzee (Taglialatela et al., 2006; Meguerditchian et al., 2012).

Regarding Broca’s area in humans, very recently, a functional segregation was proposed with Broca’s anterior part implicated in language syntax and its posterior part exclusively implicated in motor actions (Zaccarella et al., 2021). The authors argued that action and language meet at this interface. In an evolutionary perspective we propose therefore that the intentionality of primate’s communicative gesture might account for this hypothesized functional interface of actions and language prereq-
uisites, nested inside the monkeys’ perisylvian regions including Broca’s homologue and the Planum Temporale (see also: Arbib, Pika and Liebal, 2008; Corballis, 2015; Rizzolatti and Fogassi, 2017). In addition, in macaques Broca’s homologue, neuronal recordings showed populations of specific neurons activated for both volitional vocal and manual actions (Gavrilov and Nieder, 2021).

Figure 8.6. – Effect of left-/right-hand direction of two handedness types (communication vs. action) on neuroanatomical sulcus depth asymmetries (IA sulcus vs. Central sulcus). See study 4 in this present thesis.

The articulation of our results with this recent literature suggests that gestural communication may be a compelling modality for one of the multimodal evolutionary roots of the typical multimodal language system in humans and its hemispheric specialisation. It is thus not excluded that language-related frontal and temporal lateralisation might be much older than previously thought and inherited from a gestural communicative system dating back, not to Hominid origins, but rather to the common ancestor of humans, great apes and Old World monkeys, 25–35 million years ago.
8.4. Gesture and language

The theoretical implications we discussed earlier on the gestural phylogenetical roots of language and its brain specialisation have a long history. As Michael Corballis explains in “A Word in the Hand: The Gestural Origins of Language”, 2017: “One early proponent was the philosopher and cleric de Condillac (1714-1780). He was an ordained priest, and was afraid of offending the Church’s view that language was a gift from God, so he disguised his theory as a fable about two children abandoned in the desert after the Flood. At first they communicated by using bodily movements, until eventually replacing their gestures with vocal sounds.” While during centuries many accounts were proposed, it was Hewes et al., 1973 who inspired a large set of contemporary works (e.g., Arbib, 2005; Arbib, Pika and Liebal, 2008; Rizzolatti and Sinigaglia, 2008; Tomasello, 2008; Corballis, 2017), which all have in common that they favour a continuous language development instead of a discontinuous great leap.

In fact, human language shares important connections with communicative gestures. To begin with, we often gesticulate simultaneously when we speak. For example, in signing the meaning of our words, like approaching the index and the thumb when saying “small” (McNeill, 2011). Many of these speech and co-speech gesture interactions were reported (e.g., Bernardis and Gentilucci, 2006; Willems and Hagoort, 2007). Also, the mental representation of communicative gestures and articulations of phonological exercises activate Broca’s area, unlike the observation of pure motor actions that activate the left ventral motor area. Therefore, it has been suggested that both modalities might share the same integrated communication system (e.g., Gentilucci and Dalla Volta, 2008). Deaf signers are demonstrating hereby that complex language doesn’t have to be verbal. It was documented that signed languages shares similar phonological, morphological and syntactical properties with spoken languages (for reviews: Bellugi, 1991; Emmorey et al., 2002). Also, the underlying cerebral organisation of deaf signers is striking similar to those of speech in the left hemisphere (Gentilucci and Dalla Volta, 2008). For example, stroke cases of deaf subjects, showed that lesions in Broca’s and Wernicke’s areas causes aphasia as observed on hearing subjects (MacSweeney et al., 2008, Campbell et al., 2008). These perisylvian structures are also showing structural asymmetries, initially associated to speech (Campbell et al., 2008).

Furthermore, it is well known that intentional communication in infants developed first with the use of communicative gestures before their first spoken words. Deictic gestures specifically, such as pointing, seem to play an active role in the development of linguistic abilities (e.g., Vauclair, 2004; Iverson and Goldin-Meadow, 2005). Interestingly, infants use more their right hand for informative pointing than reaching actions (Cochet and Vauclair, 2010) and increases when the lexical spurt occurs contrary to manipulation handedness (Cochet et al., 2011).

As far as language evolution is concerned, scientists did not initially focus on gestural communication in nonhuman primates, but rather on vocal communication. This may be the reason why prominent discontinuous "Great Leap" theories have been developed (e.g., Berwick and Chomsky, 2016). Indeed, shared properties of lan-
guage in humans and vocal communication in nonhuman primates are hardly found (Meguerditchian et al., 2013). As writes Jane Goodall “(t)he production of sound in the absence of the appropriate emotional state seems to be an almost impossible task for a chimpanzee” (Goodall, 1986, p.125). In fact, apes lack the voluntary control of their voice and emotionally induced vocalisation are difficult to suppress (Corballis, 2017).

Corballis, 2017 further argues that “The capacity for intentional control of the voice, largely absent in the chimpanzee, must therefore have evolved after the separation of the hominin line from that leading to modern chimpanzees” (Corballis, 2017).

However, it is known that all ape species use their hands and feet but also their complete body as well as their posture and facial expression to communicate in various social contexts. For example, chimpanzees raise their arms to ask for grooming or slap the hand to the ground to threat another individual, and juveniles can touch the mother’s mouth for food begging. These kinds of gestures were extensively described in many species (see e.g., Meguerditchian et al., 2013, Meguerditchian and Vauclair, 2008 for reviews). Whereas functions of vocalisations are described as vital as reproduction, reporting danger, foraging, aggression, the functions of gestures are considered less evolutionary “urgent” (e.g., Tomasello and Zuberbuehler, 2002).

Figure 8.7. – Example for an intentional communication: the referential ‘directed scratch’ gesture in wild chimpanzees. An individual scratches a part of its body to indicate to its conspecific the precise area where it wishes to be groomed. Drawing: Adrien Meguerditchian (adapted from Pika and Mitani, 2006).

In fact, a large body of work has shown that, in contrast to controversial results from vocalisation studies (Fischer and Price, 2017), gestural communication was sharing key features of human language, like the capacity of transmitting voluntary a message to an individual in particular (“intentionality”: In Apes: Call and Tomasello, 2007, in Baboons: Meunier et al., 2012, Molesti et al., 2019), the capacity of orientating the attention of others to an exterior place or object (“referential pointing”: In apes: Leavens et al., 2004; in baboons: Bourjade et al., 2014) or the possibility of learning permanently new signal (“learning flexibility”: In Apes : Pika et al., 2005, in monkeys: :
8.5. Future perspectives

Immediate future perspectives are concerning the further exploration of the developmental questions such as “When does such an asymmetric organisation appear in nonhuman primate development” and “Does it predict later behaviour?” In this thesis, such questions were possible to be investigated in the Planum Temporale for which manual delineation tracing was possible on both the surface and the grey matter volume of this region. We were limited however in investigating such questions in other key regions of interest such as the Inferior Arcuate sulcus (i.e., a marker of the Broca’s homologue), the central sulcus and the Arcuate Fasciculus at this earlier stage of development. Those other regions required extraction of sulcus depth and of white matter track which are dependent of high quality preliminary tissue segmentation, contrary to manual delineation of region of interest. Such limitations were due to the difficulty in tissue segmentation of newborn MRI images given that the myelinisation maturation is not homogeneous across the brain at such early age. As a results, such type of tissue segmentation requires very time-consuming work of manual editing for each subject which was not feasible within the time frame of this PhD.

However, the near completion of the tissue segmentation of the white-, grey matter and the cerebrospinal fluid on these MRI images will allow the sulcus parametrization (crucial for the Broca’s homologue) and tractography for modelling the Arcuate Fasciculus.

In addition, recent data are expanding to more distributed models, taking into account several different fibre tracts and regions crucial for language processing as demonstrated by clinical cases (e.g., Catani and Mesulam, 2008) and questioning a localisationist viewpoint of language specialisation (e.g., Duffau et al., 2018). For example, the importance of regions in the interface between social cognition and communication like the Superior Temporal Sulcus and Geschwind’s territory in the Inferior Parietal Lobe are highlighted (Catani and Dawson, 2017), as well as the anterior Insula cortex and the anterior and mid-Cingulate Sulcus. Most of these structures share one fundamental feature: They are also functionally and structurally specialised towards one hemisphere, mostly the left (Toga and Thompson, 2003; Keller et al., 2011; Amiez et al., 2019). Therefore, in the future, it is of importance to take also into account other key regions of the large, distributed language network, beyond the classical perisylvian regions, such the Insula, the Cingulate Sulcus, Inferior Parietal Lobe, and the Superior Temporal Sulcus, as novel grey matter areas of interest.

A second, more methodological collaboration with Scott Love, INRAE, which also depends on tissue segmentation, concerns the creation of an average brain template at each time point in development. In this way, several general questions concerning brain development may be answered. In addition, the wider community working on nonhuman primate neuroimaging will benefit from this template as we will make it openly available. Another project line concerns the Arcuate Fasciculus in chimpanzee.
In fact, whereas perisylvian grey matter areas were studied in apes, no study focussed on the behavioural correlates of the Arcuate Fasciculus in chimpanzee. A current collaboration with tractography-experts Erin Hecht and Suhas Vijaykumar from Harvard University will advance this project.

Finally, a crucial question persists: Which cognitive process is at the heart of language processing that is shared with gestural communication? As gestural communication is already a higher order, complex and composite process, it is interesting to investigate, which function is initially related to hemispheric specialisation, which nowadays supports language processing in the brain. Suitable candidates are the “intentionality” of the behaviour, the complexity, or the hierarchical structure of the action (e.g., Arbib et al., 2008; Stout and Chaminade, 2009; Meguerditchian et al., 2013).
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ANNEXES (Articles)
A. Accelerating the Evolution of Nonhuman Primate Neuroimaging

Published article:
Accelerating the Evolution of Nonhuman Primate Neuroimaging

The PRIMatE Data Exchange (PRIME-DE) Global Collaboration Workshop and Consortium**

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Nonhuman primate neuroimaging is on the cusp of a transformation, much in the same way its human counterpart was in 2010, when the Human Connectome Project was launched to accelerate progress. Inspired by an open data-sharing initiative, the global community recently met and, in this article, breaks through obstacles to define its ambitions.

Nonhuman primate (NHP) neuroimaging carries tremendous translational promise for biomedicine (Phillips et al., 2014; Roelfsema and Treue, 2014). However, progress has been slow, as researchers face not only the many challenges that human neuroimaging has overcome but also unique obstacles that require consensus solutions. To date, the approach has remained largely piecemeal and single-lab driven, causing most NHP researchers to struggle to amass datasets consisting of even 10 to 20 subjects, whereas their human-imaging counterparts now aim for thousands.

The PRIMatE Data Exchange (PRIME-DE) was recently established to accelerate the pace of advancement (Milham et al., 2019) by promoting a culture of collaboration and open science in the NHP neuroimaging community. PRIME-DE established a repository of openly shared data in 2018, followed by a Global Collaboration Workshop (GCW) on September 5–6, 2019 at the Wellcome Trust in London. Through these efforts, the community has made substantial progress toward a global vision and here outlines its ambitious albeit eminently achievable goals. Four key domains of activity in NHP neuroimaging are considered that can dramatically accelerate progress.

**Standardizing Data Collection**

Harmonizing Data Collection Is Key for Reproducibility and Shared Data Value

Minimal Data Acquisition Specifications. There was agreement that a universal data acquisition protocol is not yet practical, but minimal specifications can be defined toward standardization. A shared lesson from the Human Connectome Project (Van Essen et al., 2013) is that the cortical sheet should be resolvable with isotropic voxels no larger than half the minimum cortical thickness (e.g., 0.5–0.6 mm voxels for macaque cortex and 0.4 mm for marmosets). Acquiring 3D T1- and T2-weighted scans is important for brain segmentation, and T1/T2 ratios can generate “myelin maps” to assist surface mapping and rapid quality checking.

For functional MRI, attainable target spatial resolutions are 1.0-mm isotropic voxels for large NHPs and 0.5 mm for smaller ones. However, these are beyond the 1.2–1.5 mm range currently employed on common 3 Tesla scanners, and manufacturers are phasing out gradient inserts previously used to boost signal-to-noise. A way forward is the adoption of more sophisticated coil systems with higher signal to noise (SNR), enhanced with acceleration methods (multiband imaging) for higher functional and temporal resolution with less acquisition time. These coils are commercially available (24-channel macaque, 16-channel marmoset) though still require customization to accommodate head posts and/or chambers.

Anesthetized Imaging. Although awake imaging is clearly the long-term aspiration for NHP imaging, it is technically challenging and requires training the subject. Thus, anesthetized imaging remains important for resting-state, diffusion, and structural imaging and benefits from minimal head motion. A key factor for establishing common practice is standardizing the anesthetic agents. Many GCW laboratories already use highly similar protocols, entailing isoflurane anesthesia for structural imaging and IV administration of dexmedetomidine (0.015–0.02mg per kg bolus or 4.5–5.0ug per kg per h infusion) to allow reduction of isoflurane concentrations to between 0.6%–1.0% to improve the functional MRI signal. Other agents are being successfully employed and might be required by researchers for scientific reasons (Flecknell, 2015). Beyond the specific agents employed, opportunities exist to advance the monitoring and control of anesthesia depth throughout scanning by logging temperature, end tidal CO2, O2 saturation, respiration rate, heart rate, and blood pressure synchronized to data acquisition.

Awake Imaging. Four identifiable challenges confront awake NHP imaging. First is the challenge of behavioral training for the scanner environment. Second, the placement of head immobilization hardware determines which brain areas are accessible with head coils. This precludes universal acceptance of a single head coil and necessitates customization or generating a range of standardized options. Third, noninvasive eye tracking provides a key control measure in awake NHPs. Finally, head and jaw movements, as well as the apparent head movement and brain distortions produced by changes in susceptibility from body and limb motion, remain a problem for awake imaging, particularly at high magnetic fields. Behavioral training and external monitoring methods, such as magnetic resonance (MR)-compatible video tracking and jaw and/or body motion sensors, can be invaluable for correcting motion. Post-acquisition...
methods (e.g., ICA-AROMA, ICA-FIX) will help; and film viewing, when appro-
priate, can decrease head motion (as re-
ported in human neuroimaging).

Opportunities for Improving Data Quality. Although using higher field
scanners is an obvious way to improve

data quality, current costs (~1 million
USD per Tesla) and operational nuances
make them relatively inaccessible to
most groups. Recent findings suggest
that iron-based contrast agents such as
monocrystalline iron oxide nanopar-
ticle (MION) can increase contrast-to-
noise ratio (CNR) and spatial specificity
at 3 T. However, this has limitations, as
the agents tend to be costly, and frequent
usage necessitates the intro-
duction of chelating agents to minimize
impact on animal welfare by long-term
accumulation of iron. Additionally,
contrast agents measure cerebral blood
volume (CBV) rather than the blood-
inequation-level-dependent (BOLD)
response, complicating comparison to
human BOLD fMRI. Unlike human MRI,
NHP MRI suffers from dramatic signal
variations from coils or other sources.
Thus, appropriate quality control strate-
gies should be implemented both for
custom and standard coils. An approach
to improve fMRI data quality is to in-
crease the number and duration of acqui-
sition sessions (Xu et al., 2018). Prospective motion correction ap-
proaches deployed in human research
(Maclaren et al., 2013) may also improve
structural imaging. Currently, the main
way to avoid motion artifacts in awake
imaging is to limit head movements (e.g.,
training or head immobilizing).

Finally, investigators identified the
need for creating and sharing NHP
“phantoms,” which would allow data-
collection sites to check and benchmark
their data-collection protocols using
a common reference as is done in hu-
man imaging. Such phantoms would
be created and made freely available
as a 3D-printed model of a given spe-
cies’ brain filled with a contrast agent
with known relaxation times to stan-
dardize signal-to-noise assessment
across sites. Phantoms could be
created for any of the primate species
(apes, marmosets, baboons, ma-
caques). Importantly, working on good
quality data acquisition beats any
post-acquisition cleaning algorithm
available and is crucial if we are to
create standard pipelines for NHP MRI
data analysis.

Animal Welfare, Regulations, and
Intellectual Property
NHP Imaging Stakeholders Are
Seeking Policy-Making Guidance
from and Working with Funding
Agencies, Professional Societies,
and the Larger Community to
Ensure Maximum Benefit and
Transparency
Animal Welfare and Regulations. NHP
neuroscience is a heavily scrutinized
and extremely sensitive area of research with
extensive ethical approval processes
and oversight. However, NHP research is
not governed by a common set of inter-
national regulations or ethical statements
(e.g., Declaration of Helsinki for human
research). National differences in NHP
research and NHP welfare regulations
are particularly problematic for efforts to
collaborate internationally. The commu-

ity agreed that addressing this challenge
going forward will benefit from additional
transparency when sharing their datasets,
including identification of the relevant
regulatory body and reference to their
published standards. Additionally, it will
be important to increase the collection
and sharing alongside MRI data of objec-
tive and evidence-based measures of an-
imal health status as metadata, which can
also provide scientific insights (e.g.,
home-cage behavioral data, eye-tracking
data, genomic information, rearing and
maintenance information, sourcing of
animals, anesthesia and maintenance values,
as relevant). National primate centers
and breeding sites can help with collec-
tion of this metadata.

Engaging the Public. Candid and trans-
parent communication with the public on
the importance of nonhuman animal
research is vital for maintaining and
increasing governmental and public sup-
port. It is not uncommon for institutions
and scientists to find themselves in a
reactive rather than proactive position,
focusing solely on the defense of their
work. Recent experience is showing that
a proactive stance raises public aware-
ness and support for animal research as
a key element of modern science and
medicine, balancing the discussion of

concerns raised by activist groups. Politi-
cians are often unaware of the impact of
the animal research occurring in their
own constituencies, which can lead to
legislation being put forward that fails to
capture the importance of scientific ad-
vances. Institutional and funding-body
press offices could better link transla-
tional developments directly to the foun-
dational research performed on labora-

tory animals because the reporting of the
fundamental animal research bases is
often unmentioned. Researchers and
their institutions can find support and
public-engagement training from groups
such as Speaking of Research (US),
Basel Declaration on Animal Research
(EU), Pro-Test Deutschland (GER), Pro-
Test Italia (ITL), Understanding Animal
Research (UK), and Gincor (FRA).

Alongside the importance of the work,
the public can learn about the balance
between benefits and harms, including
evidence-based safeguards for animal
welfare. Several institutions have
now signed the UK Concordat on
Openness in Animal Research (http://
concordatopenness.org.uk). This now
five-year-old agreement, currently signed
by 122 institutions, encourages openness
and better information sharing about
animal research. Rather than being a
generic statement on openness that will
often go unmentioned. Researchers and
their institutions can find support and
public-engagement training from groups
such as Speaking of Research (US),
Basel Declaration on Animal Research (EU), Pro-
Test Deutschland (GER), Pro-
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Test Deutschland (GER), Pro-
Test Italia (ITL), Understanding Animal
Research (UK), and Gincor (FRA).

Crediting and Intellectual Property.
In NHP research, where substantial costs
and efforts are required for training or
maintenance of a single individual, investi-
gators hold real concerns about not being
appropriately credited or being “scooped”
analytically with one’s own data. Recent
years have witnessed an increasing
acceptance of “data descriptors” or
"data papers" on resource-sharing infrastructures (Neuroimaging Informatics Tools and Resources Clearinghouse [NITRC], Zenodo) as a publication-based means of crediting data generators and encouraging sharing. Digital object identifiers (DOI) assigned to datasets can further assure the rapid identification, crediting, and tracking of datasets. However, such efforts need to be recognized by the institutions and used in promotion reviews (e.g., Declaration on Research Assessment, https://sfdora.org). This situation is problematic for the advancement of open science and must be addressed by a coordinated effort involving both institutions and funders recognizing the importance of data generation and sharing. These realities often drive investigators to hold back their newest data from sharing initiatives, instead sharing only those datasets that have already yielded publications.

GCW participants converged on a solution that moving forward, in addition to fully open sharing options, a "collaborator seeking" sharing option will be added with the following terms: (1) early sharing encouraged, but an investigator can accept or reject access requests to these data; (2) the investigative team may receive co-authorship credit on the publication (to be negotiated by the dataset holders and proposed collaborator); and (3) upon publication of the first manuscript, the data status will switch to open sharing. Additionally, GCW participants felt that the generation of a registry of ongoing studies would be immensely important for the NHP research community to avoid duplicating efforts and to foster collaboration. Finally, the issue of using shared data for commercial purposes remains unresolved. In human studies, the data generators can consent to commercial use or not, but for the NHP community, it is less clear if ownership lies with the data generator, institution, or funder.

Data Standards, Quality Assessment, and Analytic Softwares

The Adoption of Data Standards and Open Analytic Solutions Are Readily Attainable

Data Standards. There is a clear need for metadata standards in NHP data acquisition. The Brain Imaging Data Structure (BIDS) framework (Gorgolewski et al., 2016), used in the initial PRIME-DE data release, is recommended given its rapid maturation and widespread adoption in human neuroimaging, including EEG and MEG. However, the BIDS format will require revision to capture the range of metadata unique to NHPs. Minimally, species and scanning position (upright, sphinx) require specification. Metadata could also include details regarding anesthesia protocol, contrast agents, coil type (surface versus volume), head-fixation information, subspecies, age, sex, universal specimen identifiers, body weight, available genomic information, and animal origin. The NIFTI (Neuroimaging Informatics Technology Initiative) and GIFTI (Connectivity Informatics Technology Initiative) format appears to be better positioned as a framework for connectivity analyses that span surface-based representations and subcortical regions.

Quality Assessment. NHP imagers have yet to reach a consensus on quality assessment or assurance. Some datasets might be of higher quality, even if these are from fewer animals. There are also concerns that implementing high QC standards at this initial stage will stall data sharing, and analytic methods may be developed to rescue lower quality data. In the human literature, steps toward universal approaches to quantify data quality are being made (e.g., MRQC) and could be adapted for NHP imaging. However, most existing tools are optimized for human heads, which have very different tissue profiles and are imaged at lower resolution. Investigators are leveraging technical advances (e.g., multichannel segmentation, deep learning, improved templates) to break through this barrier and avoid manual correction. However, at present, visual inspection and ratings remain key steps for quality assessment and analytical validation. Given these realities, the PRIME-DE consortium has recommended sharing all data regardless of data quality and to share QC ratings for the datasets. Finally, real-time quality assessments have been recently automated in the human literature (e.g., the FRAMEworks Integrated Real-time MRI Monitoring [FIRM]) and could be adapted for NHP imaging for motion monitoring, feedback, and to assess when sufficient data have been collected.

Pipelines. There is a scarcity of end-to-end NHP image preprocessing pipeline solutions, including surface-based analyses. Investigators identified a range of open-source tools and pipelines that are available or progressing in their development, making it just a matter of time until the reliance on in-house code decreases. This process can be accelerated through establishing mechanisms for rapid communication of developments via wikis, mailing lists, technical notes, code repositories, notebooking sites, and Brainhack events. Such communication is especially important in assisting investigators from outside of NHP imaging to engage with this community’s data. Publication of methods papers is encouraged and their value should be considered in assessing a researcher’s productivity. Lastly, it is worth noting that scientists are making progress in tackling the challenges of within and interspecies alignment. These efforts are crucial not only in advancing our understanding of the NHP brain but also in creating a common terminology between researchers from human imaging and the NHP community who quite often still use different vocabularies. A critical ongoing effort by some groups attending the GCW is the alignment of imaging and digitization of the wealth of histological and tract-tracing data in NHPs and sufficient investment, such important data could be curated, helping to bridge analytical scales.

Coordinated Paradigm Design

Common Ground in Functional Imaging Creates Opportunities for Globally Coordinated Activity

Functional localizers are commonly used in human and NHP imaging, spanning retinotopy, tonotopy, object perception, somatotopy, eye movements, social cognition, and more. To date, labs have tended to use customized approaches by creating and using their own localizer stimuli, typically in a relatively limited number of subjects. Commonalities in focus areas across laboratories create
opportunities for coordinated paradigm design and data sharing. First, the simple sharing of final statistical maps (e.g., via NeuroVault, Open Science Framework, or the Brain Analysis Library of Spatial Maps and Atlases [BALSAL]) would generously allow applying meta-analytic techniques and aggregating across site information. Equally important, the sharing of functional localizer stimuli would allow harmonizing efforts and, as a result, improve the likelihood of reproducible findings, dramatically enhancing the value of shared datasets. Complementing lower-level functional localizers are naturalistic stimuli (e.g., films), which can be used to probe a range of systems, including higher-order association areas. Unfortunately, there is great variation in naturalistic stimuli across laboratories and in custom analyses that are needed to extract meaningful information from these localizers. As a first step, the community agreed that small groups will work together on obtaining coordinated localizer data for different modalities in 30 individuals as a basis for creating template-based probabilistic maps. These data will be invaluable to the broader community that often requires information on where functional fiducials reside in specific individuals. Long term, the community wants to work toward generating a collection of natural films and analytical approaches for a rapid (10–15 min) multi-faceted “primate global localizer” that could be used by many laboratories. Its usefulness will need to be validated and established alongside information from accepted localizers.

Ambitions for the Next Five Years
Over the course of the next five to ten years, the PRIME-DE GCW attendees agreed that it will be possible to collect and share structural scans from 1,000 NHPs in various species with further grassroots sharing efforts of higher quality and more extensive datasets in 200 animals. With financial support, the coordination of activities centered around localizers could yield data from 30 animals for a given localizer, as the community works toward a multi-faceted primate functional localizer. More substantial investment would allow the generation of a large-scale, multimodal resource for NHPs similar to the Human Connectome Project, possibly including developmental samples (pediatric, fetal) and metadata (genotyping and phenotyping information, etc.). The integration of digitized neuronal tract tracing data, neurophysiology (high density recordings, laminar, etc.), histology, and neuro-modulation approaches (optogenetics, electrical microstimulation, pharmacological inactivation, ultrasound, etc.) would bring unprecedented value to the resource.

Conclusion
We have synthesized a perspective put forward by the GCW meeting on the challenges and opportunities for NHP imaging and the ambitions of the community. Given the grassroots nature of the effort, the community recognized the need to meet regularly to strengthen communication and facilitate progress. Following the lead of its human counterpart, NHP imaging is unquestionably evolving toward reproducible and scalable science. To accelerate the pace of its evolution through increased collaboration, sharing, and investment, large-scale global neuroscience ventures (e.g., the BRAIN Initiative, Human Brain Project) and other funding schemes will need to support the community objectives for the next five to ten years of data generation and sharing. If the PRIME-DE GCW serves as a litmus test, exciting advances, and discoveries will become evident by global collaboration and support.

SUPPLEMENTAL INFORMATION
Supplemental Information can be found online at https://doi.org/10.1016/j.neuron.2019.12.023.

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B. Structural brain asymmetries for language: a comparative approach across primates

submitted article (in revision):
Structural brain asymmetries for language: a comparative approach across primates

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Abstract

Humans are the only species that can speak. Nonhuman primates, however, share some "domain-general" cognitive properties that are essential to language processes. Whether these shared cognitive properties of humans and nonhuman primates are the result of a continuous or convergent evolution can be investigated by comparing their respective underlying structure: the brain. Key areas associated with language processes are the Planum Temporale, Broca’s Area, the Arcuate Fasciculus, Cingulate Sulcus, The Insula, Superior Temporal Sulcus, the Inferior Parietal lobe and the Central Sulcus. These structures share a fundamental feature: They are functionally and also structurally specialised to one hemisphere. Interestingly, several nonhuman primate species, such as chimpanzees and baboons, show human-like structural brain asymmetries for areas homologous to these key-markers of functional language lateralisation. The question arises, then, for what function did these asymmetries arise in non-linguistic primates, if not for language per se? In an attempt to provide some answers, we review the literature on the lateralisation of the gestural communication system, which may represent the missing behavioural link to brain asymmetries for language area’s homologues in our common ancestor.
Introduction

“Human being: n. a man, woman, or child of the species Homo sapiens, distinguished from other animals by superior mental development and language…” (The Oxford Pocket Dictionary of Current English, Oxford University Press 2009)

This definition states the obvious: Humans are the only species able to speak, and thus, this fascinating cognitive faculty is considered as a key feature which divides us from other animals (e.g., Berwick and Chomsky, 2016). However, in recent years the conception of one holistic language faculty has been contrasted with an alternative view that language may be the results of an assembly of cognitive properties that are domain general and not specific to language (e.g., Fedorenko, 2014). Therefore, since nonhuman animals, especially primates, have been shown to share some of these “domain-general” cognitive properties, the research on nonhuman primates was reconsidered as a critical model to investigate language evolution (e.g., Fitch, 2010, Liebal et al., 2014, Fagot et al., 2019). Whether these shared cognitive properties between humans and nonhuman primates are the results of a continuous (homologies)- or convergent evolution (analogies) can be investigated by comparing their respective underlying structure: the brain. In humans, language models congruently describe a few key hubs of language processing, namely Broca’s and Wernicke’s area, and their interconnection, the Arcuate Fasciculus (Geschwind, 1970; Toga and Thompson, 2003a; Bidula & Kroliczak, 2015; Becker et al., 2021a). However, in recent years, data are expanding to more distributed models, taking into account several different fibre tracts and regions crucial for language processing as demonstrated by clinical cases (e.g., Catani and Mesulam, 2008) and questioning a localisationist viewpoint of language specialisation (e.g., Duffau et al., 2018). For example, the importance of regions in the interface between social cognition and communication like the Superior Temporal Sulcus and Geschwind’s territory in the Inferior Parietal Lobe are highlighted (Catani & Dawson, 2017), as well as the anterior Insula cortex and the anterior and mid-Cingulate Sulcus. Most of these structures share one fundamental feature: They are functionally and also structurally specialised towards one hemisphere, mostly the left (Toga and Thompson, 2003; Keller et al., 2011; Amiez et al., 2019). Specifically, “functionally lateralisation” refers to a more pronounced activation in one hemisphere than the other. “Structural lateralisation” refers to a more pronounced volume, size, surface measurements or neuron density of a given region in one hemisphere than the other. Although the link between structural and functional asymmetry remains unclear and questionned (e.g.,
Gerrits et al., 2021; Tzourio-Mazoyer et al., 2018), most authors usually consider that structural asymmetry (“the size of the roads”) of these regions might reflect the functional asymmetry (“the traffic”) for language tasks (Dehaene-Lambertz et al., 2002; Catani et al., 2007; Keller et al., 2011).

Thus, the fundamental question of “how language lateralisation has evolved” is more topical than ever in the light of the aforementioned findings about language organisation in the brain. This is where comparative studies on our primate cousins are of importance. In fact, “evolution” implies that language has developed progressively (e.g., as exaptations from preexisting cognitive functions) and intermediate steps may be found across common ancestors from primate lineage. However, because brain tissue hardly fossilises, one fruitful way of trying to find such intermediate steps is the comparison of brains between primate species including humans to infer potential features inherited from their shared common ancestors. In other words, one can determine, which brain architectures and behaviours are shared between us and other primates, suggesting its pre-existence before the emergence of our species. Comparative brain approaches for primate species have particularly focussed on neuroanatomy, given the well-known limitation for functional studies in apes and monkeys (e.g., techniques, ethics, sample size, reproductivity). The advent of non-invasive techniques such as Magnetic Resonance Imaging (MRI) favours in-vivo acquisitions, on anesthetised subjects, allowing no limitation in terms of sample sizes and species diversity (Poirier et al., 2021). As a results, primate brain research has benefit in the recent year from considerable increase of available MRI databases on large cohorts in many primate species, including macaques: Prime-De, (Milham et al., 2020) and chimpanzees: www.chimpanzeebrain.org (e.g., Hopkins et al., 2008). Just as in human brain research, research on primate brain anatomy allows morphological quantification of regions in each hemisphere and determine possible interhemispheric asymmetries. In this quest, an increased body of evidence highlights that different nonhuman primate species, such as chimpanzees or baboons, show human-like structural brain asymmetries for areas homologous to key-markers of functional language lateralisation (e.g., Hopkins et al., 2015; Marie et al., 2018).

Thus, the question arises for which function these asymmetries in non-linguistic primates have developed, if not for language per se? In humans, handedness for manual actions was for a long time considered as such a behavioural reflection of a language related brain lateralisation (e.g., Knecht et al., 2000). However, more recent studies indicate that direction of handedness for manual actions poorly predicts language lateralisation, especially in left-handed humans. Indeed, 96% of right-handers and also 70% of left-handers have their left
hemisphere functionally specialised for most language functions (e.g., Knecht et al., 2000). In fact, handedness for manual actions was shown associated to the contralateral lateralisation of the motor hand area within the Central Sulcus, rather than key language areas (Amunts et al., 2000). Altogether, it is now acknowledged that direction of handedness might be independent from direction of language lateralisation (Groen et al., 2013; Mazoyer et al., 2014; Ocklenburg et al., 2014). As a result, comparative research on handedness for manual actions across primates might not be suitable for investigating phylogenetical origins of hemispheric language specialisation. To do so, it has been suggested that studying manual lateralisation of gestural communication in nonhuman primates - and not handedness for manipulative actions - might constitute a more fruitful approach (e.g. Meguerditchian et al., 2013; Hopkins et al., 2012). In fact, following the evolutionary framework about the gestural origins of language (e.g., Hewes, 1973), gestural communication system in nonhuman primates were found to share key features of domain general processes, important for language, such as intentionality, referentiality and learning flexibility (e.g., Tomasello, 2008; Meguerditchian & Vauclair, 2014; Molesti et al., 2020). Interestingly, production of communicative manual gestures has been found highly lateralised in favour of the right-hand in both baboons and chimpanzees. In contrast, the handedness patterns for non-communicative manual actions in chimpanzees and baboons were found different from those found for communicative gestures at both the populational but also the individual level (Meguerditchian et al., 2013). These findings supported the idea that gestural communication in nonhuman primates may be related to a specific lateralised system for communication, which might be different than handedness for manipulative actions (Meguerditchian et al., 2014). Therefore, there is a necessity of taking stock of what the work on neuroanatomical correlates of gestural communication in nonhuman primates has provided, in order to test its supposed continuity with language lateralisation.

In the present paper, we aimed to review the literature comparing structural brain asymmetries across primates for areas related to language in humans. We will focus on the classical perisylvian language regions, namely the Planum Temporale, Broca’s Area and the white matter tract that interconnects these two regions: The Arcuate Fasciculus. In this review, it is of importance to take also into account other key regions of the large, distributed language network, beyond the perisylvian regions, such the Insula, the Cingulate Sulcus, and the Superior Temporal Sulcus (STS) as novel grey matter areas of interest. Finally, we will consider the Central Sulcus (CS), which delimitates the primary motor from primary somatosensory cortex, and include thus the mouth and lips motor areas as well as the motor hand area related to handedness (see Figure 1). After briefly describing their functions, we will first
review their structural and functional lateralisation in humans including infants to discuss whether structural markers can predict the functional lateralisation of language. In a next step we will compare these findings with non-human primates and discuss whether this asymmetric organisation is shared between species. Finally, we addressed the following question: If such brain lateralisation is shared with our non-linguistic primate cousins, for what behavioural functions did it evolve, if not for language? In an attempt to give some elements of responses, we propose to review the literature about the lateralisation of the gestural communicative system, which could potentially constitute the ideal missing behavioral link with brain asymmetries for language in our common ancestor.

Figure 1. Illustration of the reviewed key structures in a monkey brain. In brown: Broca’s area, in yellow: the Insula, in red: the Arcuate Fasciculus, in blue: the Central Sulcus, in green: the Planum Temporale, in light red: the Planum Parietale, in grey: the Superior Temporal Sulcus, in purple: the Cingulate Sulcus.

Planum Temporale

The most emblematic marker of the lateralised language organisation is the Planum Temporale (PT) which is located within the Sylvian fissure and which is part of the auditory association cortex (Galaburda et al., 1978) and Wernicke’s area (Mesulam et al., 1998). In adults, left hemispheric lesion of this region resulted in severe language comprehension and production deficits (Wernicke, 1874; Dronkers et al., 2004; Borovsky et al., 2007). Therefore, many studies have shown the particular functional significance of the PT in the left hemisphere in a variety of auditory language processing (Shapleske et al., 1999), including the main perception component of the audio-motor loop for phonological processing (Vigneau et al., 2006). Interestingly, also in preverbal new-borns the functional implication of the left PT was highlighted from birth on (Dehaene Lambertz et al., 2002; 2010; Mahmoudzadeh et al., 2013). In the pioneering work of Geschwind and Levitsky (1968) the PT was shown to be anatomically asymmetric: In 100 post-mortem brains, 65% of the left PT was larger than the right, which was confirmed by in-vivo MRI studies (Shapleske et al., 1999) and also highlighted in early development (Post-mortem Infants: Wada, 1975; Witelson, S.F., Pallie, W., 1973. In-vivo MRI infants: Glasel et al., 2011; Hill et al., 2010; Dubois et al., 2008a; 2010a; foetuses: Chi et al., 1977a;b). These asymmetries are later increasing during development, which was associated with language development (Wada 1975; Dehaene-Lambertz et al., 2002; 2010; Mahmoudzadeh et al., 2013). The PT asymmetry is therefore seen a marker for the human unique innate readiness to acquire language (eg. Dehaene-Lambertz et al., 2002).

Indeed, in adults a direct relationship was shown between the left PT’s size and functional asymmetry of language tasks (Josse et al., 2003; 2006). In addition, an absence or reversed PT asymmetry has been linked to several language related pathologies like dyslexia (Gauger et al., 1997; Altarelli et al., 2014). This function-structure relationship is however debated (Jäncke & Steinmetz 1993; Dorsaint-Pierre et al. 2006; Eckert et al. 2006; Keller et al. 2011; Greve et al. 2013; Kolinsky et al. 2014; Tzourio-Mazoyer & Mazower, 2017; Tzourio-Mazoyer, Crivello & Mazoyer 2018; Ocklenburg et al., 2018; Gerrits et al., 2021). For example, Greve et al. (2013) showed that regardless of the functional hemispheric dominance for language, the structural PT volume asymmetry is left biased. In contrast, Ocklenburg et al. (2018) found that a higher density at a microstructural level of the left PT was associated with faster processing of auditory speed in the same area, as shown in EEG. More recently, Tzourio-Mazoyer et al. (2018) demonstrated that, although the structural PT asymmetry is not predictive
of its functional counterpart in a language task, an adjacent auditory area at the end of the Sylvian fissure is.

Several studies in nonhuman primates also showed striking human-like PT asymmetries in their homologous regions. Manual delineation of post-mortem brains (Gannon et al., 1998), in-vivo MRI scans (Hopkins et al., 1998; Hopkins & Nir, 2010) as well as voxel-based morphology on MRI scans (Hopkins et al., 2008), showed larger left PTs in chimpanzees and in apes in general (Cantalupo et al., 2003). Recently, in-vivo MRI studies on adult and newborn baboons with manual PT delineation extended this finding to a shared feature between Old world monkeys and humans (Marie et al., 2018; Becker et al., 2021c;d). Interestingly, the asymmetry strength increased with age in this longitudinal study (Becker et al., 2021c). The results are questioning the PT asymmetry 1) to be unique in humans and 2) to be marker for language development in newborns. Rather the PT asymmetry might have evolved for a cognitive function shared between Old world monkeys, apes and humans, which is at the core of language processing in humans. A potential candidate related to such a function may be communicative gesture. Indeed, Meguerditchian et al., (2012) highlighted a relation between Planum Temporale grey matter volume asymmetry and hand preference for communicative gesture in chimpanzee. Moreover, the left PT asymmetry was also found related to handedness for tool-use but not for handedness for manipulative actions in chimpanzees (Gilissen and Hopkins, 2013).

Broca’s area

Broca area and its left hemispheric specialisation was historically considered as the centre of speech production (Broca, 1861) This modular view of language neural bases was progressively questioned by the view that language involves a plastic and large distributed network (Hickok & Poeppel, 2007; Duffeau et al., 2018) and even implicates the two hemispheres. However, it is still well acknowledged that Broca area in the left hemisphere remains a key knot for language specialisation within its neural distributed network (eg. Friederici, 2017). Interestingly, complementary work thereby highlighted Broca’s area as lateralised interface between speech and multimodal motor integration including gesture and mouth mouvements (eg. Gentilucci & Volta, 2008). Broca is also known for its involvement in motor planning, sequential and hierarchical organisation of behaviours, including syntax (Koechlin & Jubault, 2006), tool-use (Stout and Hecht, 2017) and sign language production.
including thus manual and oro-facial gestures (Emmorey et al., 2004; Campbell, MacSweeney, & Waters, 2008). In infants, speech perception activates Broca’s area from very early development on as highlighted in MEG or functional MRI studies (e.g., Imada et al., 2006; Dehaene-Lambertz et al., 2006; 2010). This activation before the babbling stage suggested that activity of this area is not due to motor learning but might drive learning of complex sequences (Dehaene-Lambertz et al., 2006).

In contrast to the PT (see section above), a clear structural leftward asymmetry has not been reproducibly demonstrated (Keller et al., 2009; Sprung-Much et al., 2021), which may be due to natural variability between subjects in sulcal contours defining this area (Keller et al., 2007; 2009). Cytoarchitectonic analyses however reported a leftward asymmetry of some parts of area 44 and/or area 45, which together form Broca’s area (Scheibel, 1984; Amunts et al., 1999; 2003). In contrast, other accounts state a rightward asymmetry for area 45 grey matter, which gets reduced during aging, especially due to a loss in the right hemisphere (Kurth et al., 2020). In development, an early structural primacy of right-sided dendrite systems shortly after birth and a progressive shift to left-sided primacy during years 3 to 6 was highlighted and related to critical periods for language acquisition (Simonds and Scheibel, 1989). A second study found leftward asymmetries on the cellular level very early from 1-year old infants on (Amunts et al., 2003), which increased into an adult-like leftward asymmetry at 5 years for area 45 and 11 years for area 44. This maturational effect was suggested to be influenced by language practice and thus, the interhemispheric asymmetry of this area would continue to change throughout life (Amunts et al., 2003). Interestingly, because area 45 supports semantic processes and area 44 subserves syntactic processes in adults, some see in this maturational difference a neural underpinning of the earlier onset of semantics than syntax in children (Friederici, 2017).

In great apes, a homologous region was documented in several studies, which described the precentral inferior sulcus, the inferior frontal sulcus and the fronto-orbital sulcus as common borders of Broca’s homologue (eg. Cantalupo & Hopkins, 2001; Keller et al., 2011; Hopkins, 2017). Like in humans, inquiries about Broca’s area’s structural asymmetry on a population-level remain inconsistent in apes, due to interindividual variation in location and cytoarchitecture (Schenker et al., 2010). Leftward lateralisation was found at a macrostructural level (Cantalupo & Hopkins, 2001) but not at a cytoarchitectonic level in a relative smaller sample-size (Schenker et al., 2010; but see also Graic et al., 2020). In monkeys, no data of structural asymmetry for this region has been reported so far. In fact, determining Broca’s homologue is challenging, because the common borders of Broca’s homologue in apes are
absent in monkeys. Nevertheless, we know from few detailed cytoarchitectonic studies in macaques, that the two parts of Broca’s area 44 and 45, are respectively located in the fundus and lower caudal/posterior bank-, and on the rostral/anterior side, of the most ventral part of the inferior arcuate sulcus IAS (Petrides, 2005a;b; Belmalih et al., 2009). Electric stimulation of this region elicited oro-facial and finger movements. Therefore, together with cytoarchitectonic similarities, the region anterior to the ventral part of the IAS was proposed as an equivalent area 44 in macaques (Petrides, 2005b nature). Recent studies even reported that Broca’s homologue’s activation preceded voluntary trained production of a vocalisation after intensive operant conditioning in juvenile rhesus monkeys (Hage and Nieder, 2013). Moreover, the use of positron emission tomography (PET) in 3 captive chimpanzees has revealed that begging food from a human by using either gestures, atypical attention-getting sounds, or both of them simultaneously, activated a homologous region of Broca’s area (IFG) predominantly in the left hemisphere (Taglialatela et al., 2008). Some functions associated to Broca’s homologue’s laterisation in nonhuman primates have been proposed in relation to tool use processing and communication gesture production. Regarding tool use, chimpanzees that performed better a tool-use task with their right hand showed a greater left-lateralisation of Broca’s homologue (Hopkins et al., 2017). Such a link might be attributed to the typical Broca’s function described in humans, namely hierarchical organisation of behaviours involved in tool use (e.g., Koechlin & Jubault, 2006; Stout and Hecht, 2017). Regarding gestural communication, Meguerditchian et al., (2012) highlighted a relation between Broca’s homologue grey matter volume asymmetry and hand preference for communicative gesture in chimpanzees. Similarly, in a recent study in baboons, we showed that variation of hand preference for communicative gesture - but not for non-communicative manipulative actions - is related with anatomical variation of Broca’s homologue. Indeed, the right Broca’s portion of the IAS is deeper than the left for baboons communicating with their left hand and vice versa (Becker et al, 2021b).

Arcuate Fasciculus

The Arcuate Fasciculus (AF) is a bundle of white matter, which arches dorsally around the Sylvian fissure, interconnecting Broca’s area in the frontal lobe with the Planum Temporale in the temporal lobe (e.g., Catani and Thiebaut de Schotten, 2012). It was highlighted that the connectivity between language areas, due the AF, is crucial. For example, the integrity of the
AF might be more important for lesion recovery (e.g., strokes) that the integrity of grey matter regions that it is connecting (e.g., Duffau, 2016). In addition, as neurological cases have shown, the AF plays a key role in language processing in the left hemisphere, with lesion of the direct pathway causing conduction aphasia (e.g., Catani and Mesulam, 2008), also in deaf signers (Metellus et al., 2017). The AF is already present at birth (Dubois et al., 2016) but matures slowly until late childhood (Brauer et al., 2013, Dubois et al., 2016). In contemporary language models, the AF (or also called “Dorsal Pathway“) is often opposed to the „Ventral Pathway“, which interconnects roughly the same regions, but travels ventrally around the Sylvian fissure (Hickok and Poeppel, 2004?). In contrast to the AF the “Ventral Pathway“ matures more rapidly in development and was also described to be phylogenetically more ancient (e.g., Brauer et al., 2013; Friederici, 2017). The late maturing of the AF is proposed to be due to the frontal portion, which connects to Broca’s area and is only fully myelinated by the age of 7 (Brauer et al., 2011; Brauer et al., 2013). In fact, controversy persists whether this portion is already present at birth (Dubois et al., 2006; 2009; 2016; Perani et al., 2011; Friederici 2012 frontiers).

Regarding lateralisation, the human AF was shown larger in the left hemisphere for a number of macroscopic and microscopic measurements like the number of streamlines, volume of the tract, fibre density and mean fractional anisotropy in 60% of normal adult humans. The remaining 40% of the adult population shows either a reduced lateralisation to the left (20%) or not lateralisation at all (20%) (Büchel et al., 2004, Nucifora et al., 2005, Powell et al., 2006; Catani et al., 2007; Thiebaut de Schotten et al., 2011; Takaya et al., 2015). In early development, the leftward AF is the most asymmetrical region of the developing white matter (Dubois et al. 2009; Liu et al., 2010, but see also Song et al., 2015). Interestingly, the early leftward asymmetry in newborns was correlated with later language capacities in children (Lebel and Beaulieu, 2009; Lopez-Barroso et al., 2013; Salvan et al., 2017). Catani et al., (2007) argued that the AF’s asymmetry represents a better structural marker for functional language specialisation than the Planum Temporale asymmetry (Catani et al., 2007). This structure-function relationship is however debated (Propper et al., 2010; Zhu et al., 2014; Silva & Citterio, 2017; Gerrits et al., 2021; Verhelst et al., 2021). For example, Verhelst et al. (2021) demonstrated in a fixel based analysis, that the structural AF asymmetry did not differ between subjects with either right or left functional language hemispheric dominance.

Axon tracing in monkey brains and diffusion MRI in chimpanzee and monkey brains have highlighted the existence of the Arcuate Fasciculus across primates that interconnects frontal and temporal areas (Schmahmann and Pandya, 2006; Petrides and Pandya, 2009;
Petrides, 2014; Rilling et al., 2008, Rilling et al., 2011; Frey et al., 2014; Eichert et al., 2019; Barrett et al., 2020; Balezeau et al., 2020; Rocchi et al., 2021). It is to date debated however, to what extent frontal and temporal connections, its strength as well as lateralisation of this pathway differ between primate species. In fact, recent findings speak for a rather conserved organisation across primates (for a review: Becker et al., 2021a). Therefore, latest functional results suggest that language abilities allowing humans to name, conceptualize and thus better remember sound (Schulze et al., 2012) would be shared across primates (Rocchi et al., 2021). In order to highlight anatomical differences across primates, which could explain the human uniqueness for language, several authors conclude that the left AF lateralisation is the crux of the human-specific distinction (Eichert et al., 2019; Balezeau et al., 2020; Rocchi et al., 2021). In fact, Rilling et al. (2008) did not find any AF asymmetry in three macaque and four chimpanzee subjects. However, by adding more chimpanzee subjects, the authors were able to report a left lateralised AF, which was still weaker than in humans (Rilling et al., 2012). This result remained unique regarding AF lateralisation in nonhuman primates (Eichert et al. 2019, Balezeau et al., 2020; Rocchi et al., 2021). In fact, this inconsistency across the literature about the presence or not of population-level leftward AF bias might be explained by the small sample size (i.e., only few subjects) usually included in those AF studies in apes, which makes difficult to infer any bias at population-level. Only studies including much more subjectional sample size of subjects would help elucidate this debate.

**Insula**

The Insula cortex lies in the depth of the Sylvian fissure, which separates the temporal lobe from the parietal and frontal lobes. The anterior part of the Insula is hereby implicated for different language processing functions (General: Wernicke, 1874; Dronkers et al., 1996, Oh et al., 2014; Auditory processing: Bamiou et al., 2003; Motor aspects: Ackermann and Rieker, 2004; Syntax: Friederici et al., 2018; Merge: Zaccarella et al., 2015; sign language: Metellus et al., 2017). Interestingly, the Insula seems to be particularly involved in motor planification of speech as seen in pathologies (Dronkers et al., 1996; Ackermann and Rieker, 2004). Further, Loevenbrueck et al., (2005; 2008) highlighted in adults that prosodic pointing gesture activates Broca’s area as well the left anterior Insula (Loevenbruck et al. 2005; 2008).

Moreover, at the structural level, the volume asymmetry of this region may be associated to hemispheric dominance for language. In fact, Keller et al., (Keller et al., 2011)
found that the size of the Insula could predict functional lateralisation for language in the same hemisphere in the majority of individuals. Therefore, the Insula was proposed as a more reliable marker for functional language specialisation than the Planum Temporale (Keller et al., 2011; Chiarello et al., 2013). Although little is known about the functional implication of the Insula during language development in new-borns and infants, several studies highlighted an early lateralisation of the Insula towards the left hemisphere (Dubois et al., 2010). Thanks to all the aforementioned data, the (anterior) Insula got established as region of interest for studying linguistic (motor) processing. Additionally, the anterior Insula comprises Von Economo and Fork neurons (Von Economo, 1926) that were a long time thought to be uniquely human and implicated in social awareness. Therefore, the insula VEN and Fork neurons are often used for theories about the social origins of language (Evrard et al., 2018).

While larger in humans, the insular cortex also exists in apes and monkeys, where especially the anterior portion expanded during primate brain evolution (Bauernfeind et al., 2013). Von Economo neurons, which were thought to be exclusive to apes (Nimchinsky 1999), are also present in the anterior insular cortex of monkeys (Evrard et al., 2012; 2018). The authors argue that two distinct insular regions could be implicated in monkey communication (Evrard et al., 2018). First, a specific sensory-motor organisation for body parts in one part of the anterior Insula (the Idfa region) was found. Electric stimulation of this region elicited vocal cord movements in macaques. This region happens to be juxtaposed to a dorsal region, which receives inputs from area 44 (Part of Broca’s Area). Together the two regions could be homologous to the human anterior insula, implicated in several language processing functions (see above). Second, Von Economo and Fork neurons in another part of the anterior insula (the Ial region) are projecting into a region of the thalamus (PAG), that is involved in vocalisations (Evrard et al., 2018). However, the structural lateralisation of this region was poorly investigated in nonhuman primates. One rare study comparing the Insula structure between a handful of different primate species subjects, demonstrated that the anterior portion of the Insula, in which Von Economo neurons where found, displayed a human unique left asymmetry (Bauernfeind et al., 2013). Further studies with larger sample size are needed to investigate whether the Insula and particularly its anterior portion is structurally lateralised in non-human primates in relation to planification of communication, especially gesture.

_Cingulate Cortex/Sulcus_
The Cingulate Sulcus lays in the medial part of the cerebral cortex delimited ventrally by the Cingulate cortex and dorsally by the paracentral lobe and the superior frontal cortex. Its anterior part is considered as a hub for domain general cognitive processing like counterfactual thinking, mentalising and language including cognitive control on signals production (Toga and Thompson, 2003b, Amodio and Frith, 2006; Loh et al., 2017; 2020). Pioneer studies regarding language processes have shown that for the anterior and midcingulate cortex, 1) stimulations are evoking orofacial and tongue movements (Tailerach et al., 1973) and 2) lesioned patients experience akinetic mutism, associated with an absent motivation to speak (Ackermann and Ziegler, 1995). Little is known about the Cingulate cortex concerning direct language development. Rare results come from Loevenbruck et al. (2008) highlighting, as in adults, the functional neuroanatomical activation of the left anterior Cingulate cortex, besides Broca’s area and the Insula in communicative pointing gestures (Loevenbruck et al., 2008). However, the anterior Cingulate cortex was prominently shown to be important for joint attention in both adults and infants. Joint attention is considered a prerequisite of the theory of mind as well as a prelinguistic communication act (Mundy et al., 2018; Benga et al., 2005). Interestingly, the hand, mouth and tongue motor representations are grouped together around the caudal end of every vertical sulci departing from the Cingulate Sulcus (Amiez & Petrides, 2014), suggesting its key implication for the multimodal language system. In addition, 50% of human subjects present a Paracingulate Sulcus, located more rostrally above the anterior and Midcingulate Sulcus (Ide et al., 1999).

The presence of the Paracingulate Sulcus is lateralized in the human brain with nearly 70 percent located in the left hemisphere (Aboitiz et al., 1999; Amiez et al., 2019). This lateralisation is influenced by genetic factors and by the in-womb environment (Amiez 2018 scientific reports). At the functional level, this human asymmetry was shown to be correlated with the involvement of the left Cingulate cortex in language tasks in right-handed subjects (Paus et al. 1996; Toga and Thompson, 2003b).

Some authors suggested that the anterior and Midcingulate cortex might have also played a role in language evolution. Loh et al. (2017) hypothesised the existence of an evolutionary conserved ventrolateral frontal (around Broca’s region) and dorsomedial frontal (roughly the Midcingulate cortex) network which enables cognitive control of vocalisations. In fact, it is known that innate reflexive vocalizations like screams’ and ‘shrieks’, are associated with the “cingulate vocalization pathway” (Jürgens and Pratt, 1979). In fact, the “cingulate vocalisation area” in the anterior and Midcingulate cortex are connected 1) to the periaque ductal gray, which directly projects to premotor nuclei in the brainstem and controls laryngeal...
motoneurons, which elicits vocalisations. And 2) to the facial motor nuclei to also produce affective facial movements (Loh et al., 2017). In addition, in nonhuman primates’ innate calls can be evoked by anterior and Midcingulate cortex stimulations (Jürgens and Ploog, 1970) and lesions impair the production of calls (Aitken et al., 1981) similar as in humans. Additionally, as in the Insula cortex (see above), large spindle shaped Von Economo neurons are present in the anterior Cingulate cortex in humans, apes and other mammals (Allman et al., 2010; Nimchinsky et al., 1999; Hakeem et al., 2009). Together with the presence of Von Economo neurons in the anterior Insula, it was proposed that Von Economo neurons may be implicated in primate communication (Evrard, 2018). In contrast to the Insula cortex, no Von Economo neurons were found in the monkey’s Cingulate cortex yet. According to a recent comparative study including macaques, baboons, chimpanzees and humans, the Cingulate Sulcus shows a highly conserved morphological antero-posterior organisation of vertical sulci or their precursor “dimples” (Amiez et al., 2019).

Whereas, surprisingly, no structural asymmetries data on the Cingulate Sulcus are available so far in humans, significant population-level leftward asymmetries were found in the anterior portion of the Cingulate Sulcus in chimpanzees, whereas significant rightward biases were found in its posterior portion (Hopkins et al., 2021). In contrast to humans, no population-level lateralisation for the presence of the Paracingulate Sulcus was found in chimpanzees (Amiez et al., 2019). Nevertheless, interindividual variation of the presence or absence of a Paracingulate Sulcus and variability of the intralimbic sulcus was associated with the production of attention-getting sounds and right handedness for gestural communication in chimpanzees (Hopkins et al., 2021). It is therefore not to be excluded, that the Cingulate Sulcus could be linked to precursors of human language such as communicative gesture and vocalisations.

**Superior Temporal Sulcus (STS)**

The Superior Temporal sulcus (STS) is a long fold separating the superior from the middle temporal lobe. It was shown important for a variety of social cognition tasks important for communication (e.g., Deen et al., 2015; Belin et al., 2000), containing both specialised regions for a particular task and regions that respond to several tasks simultaneously (Deen et al., 2015). In fact, specialised areas of the STS have been shown implicated in the perception of voices in the right hemisphere (Belin et al., 2000), faces (Pitcher et al., 2011), biological
motion (Pelphrey et al. 2005), audiovisual integration (Taylor et al., 2006) and in the theory of mind (Ciaramidaro et al., 2007; Vander Wyk et al., 2009). Regarding speech perception in particular, three temporal voice areas are dispatched symmetrically in both hemispheres along an anterio-posterior gradient (Bodin et al., 2018). Distinct areas of the STS have also been implicated in language processing in hearing and deaf subjects especially in the left hemisphere (e.g., Vigneau et al. 2006; Fedorenko et al. 2012; Moreno et al., 2018). In children, responses to voices in the STS and STG are strongly right-lateralised, an asymmetry which decreased with age (Perani et al., 2011; Bonte et al., 2013). This finding suggested that newborns rely for speech processing more on prosodic information, known to be processes in the right hemisphere, than for phonological information, processed in the left hemisphere (see also Brauer et al. (2008) for a right hemispheric STG temporal primacy in children in contrast to adults). Interestingly, together with Broca’s area, the posterior Superior Temporal Sulcus is proposed to constitute the neural network supporting syntactic processes (Friederici, 2017), which, until the age of 10, does not process syntax and semantics independently (Skeide et al., 2014).

Regarding structural asymmetries, the left STS was shown longer than the right, but matures more lately, as seen in preterm newborn infants (Chi et al., 1977a; Dubois et al., 2008; 2010; Leroy et al., 2011; Leroy et al., 2015). In addition, the right STS was found to be deeper than the left STS in a portion ventral to Heschl’s gyrus, called the ‘‘STAP’’ (Superior Temporal Asymmetrical Pit, Leroy et al. 2015; Glasel et al. 2011; Bodin et al., 2018). This robust asymmetry is irrespective of age, handedness and language lateralisation, suggesting a strong genetic influence (Glasel et al., 2011; Bonte et al., 2013; Leroy et al. 2015). Functional correspondence was found between its deepest point and location of the voice sensitive peak (Bodin et al, 2018). Several sulcus interruptions “plis de passage”, are more present in the left STS, probably resulting from stronger white matter fibers passing underneath the STS (Le Guen et al., 2018). The aforementioned results highlight the STS’s implication in communication through the direct link of language perception and the indirect link with diverse social cognition tasks, which are crucial for complex language processing. This makes the STS and its asymmetric structure a promising key area in comparative studies in order to search for language prerequisites, shared between primate relatives.

The STS was intensively studied in macaque monkeys and shown to be one main hub in the social interaction processing network, where it mapped onto a fine-grain pattern of object, body and face selectivity (Sliwa and Freiwald, 2017). Indeed, its implication in a variety of social cognition tasks was demonstrated. This includes gaze following and joint attention.
(e.g. Marciniak et al. 2014) as well as facial movements in the upper STS (e.g. Fisher and Freiwald, 2015). In addition, the mid-STS in macaques was recently hypothesized to be equivalent of the human TPJ area, important for the theory of mind, because it was active for predicting social situations (Roumazeilles et al., 2020) and because macaques living in larger groups demonstrate an increased grey matter of this area (Sallet et al., 2011). Regarding especially communication, similar to humans, voice and face patches were also found in the monkey’s STS (Ghazanfar et al., 2008; Petkov et al., 2008; Beli et al., 2018; Bodin et al., 2020; 2021). In fact, recently it was demonstrated that audiovisual integration happened in a distinct region in the anterior fundus (Khandhadia et al., 2021). The Superior Temporal Asymmetrical Pit “STAP” was not robustly shown to be present in chimpanzees, suggesting a human specific landmark of perisylvian organisation, which was related to human specific social cognition and communication (Leroy et al. 2015). According to results presented at conferences, structural rightward STS depth asymmetries were also found present in adult and juvenile baboons, within a portion that may overlap with the STAP in humans. Interestingly, preliminary results in baboons suggest that the strength of this rightward STS asymmetry varies according to social cognition proxies such as social group size and gestural communication’s right-handedness (Meguerditchian et al., 2016; 2021).

**Inferior Parietal Lobe**

The Inferior Parietal Lobe or “Geschwind’s territory” comprising the angular and the supramarginal gyrus, was demonstrated as essential in language processing, connecting indirectly to primary language areas (such as the Planum Temporale or Broca’s area). For example, it was shown to be involved in episodic memory retrieval of words (Vilberg and Rugg, 2008), or verbal working memory (Jacquemot and Scott, 2006), but also in tool-use (e.g., Stout and Chaminade, 2012; Hecht et al., 2015). The Inferior Parietal Lobe is one of the latest to myelinate in development (Flechsig, 1901) and was related to the emergence of language in evolution (e.g., Geschwind, 1965) and in development (e.g., Catani and Bambini, 2014). The Inferior Parietal Lobe includes the Planum Parietale which lies in the supramarginal gyrus, in the ascending portion of the Sylvian fissure, next to the Planum Temporale (Jäncke et al., 1994). The Planum Parietale is implicated in dyslexia and communication disorders (Gannon et al., 2005) and processing voice spectral information (Lattner et al., 2005). Adaptation during primate evolution of this area and its connectivity may provide the capacity of enhanced visual
analysis of moving images that is important for tool handling and control (Vanduffel et al., 2002; Grefkes and Fink 2005; Orban et al., 2006). But also, due to its anatomical position, this region is a zone of convergence and integration of sensory and motor information, via the fronto-parietal network (Budisavljevic et al., 2021). In fact, the connection between Broca’s area and the Inferior Parietal Lobe is right-lateralised, in contrast to the left lateralisation of the Arcuate Fasciculus (see above). In addition, the Inferior Parietal Lobe inhabits mirror neurons that fire not only during motor execution, but also when observing actions performed by others, and might therefore lead to action understanding and language evolution (e.g., Arbib, 2005; Rizzolatti and Sinigaglia, 2010).

Due to the aforementioned data, the Inferior Parietal Lobe is a key-region for investigating the lateralised links between actions, tool-use and language evolution. A structural asymmetry of this area was found in the Planum Parietale. It showed a rightward asymmetry in both right-handed males and left-handed females, which was not correlated with the Planum Temporale asymmetry, indicating functional independence (Jäncke et al., 1994). Another structural asymmetry was found for the parietal operculum, which constitutes the gyrus directly above the Planum Temporale as part the supramarginal gyrus (Eickhoff et al., 2006). It shows a leftward asymmetry, especially for right handers (Habib et al., 1995).

Regarding connectivity, tool-making skills elicited plastic remodeling of fronto-parietal white matter projections from the right Inferior Parietal Lobe into the right Broca’s area (Hecht et al., 2015).

Because of the potential overlapping of brain circuits for tool-use and language, nonhuman primate brain studies have focussed on the Inferior Parietal Lobe. A potential interaction might lay in the semantic knowledge important for both language and tools to acquire the skill necessary to perform these actions (Johnson-Frey, 2004; Lewis, 2006; Stout and Chaminade, 2012). In this view, modifications of circuits that subserves gestures and imitations may have paved the evolutionary way for language and tool use in humans (Lewis, 2006), with the Inferior Parietal Lobe in its heart. Recently, Cheng et al. (2021) found that leftward rostral- and rightward caudal inferior parietal structural asymmetries connecting to several areas related to tool-use in humans (Lewis, 2006), were similar in chimpanzees and humans but not present in macaques. This finding could be related to human-like leftward asymmetries of the parietal operculum which were also reported in chimpanzees and related to tool-use but not nontool-use motor actions (Gilissen and Hopkins, 2003). To fulfill tool-use learning, humans require a degree of bodily awareness to match during practice variation in kinematic detail with the desired outcome. Similar awareness is required for other animals on
the Mirror Self-Recognition test (Anderson and Gallup, 2015), which also some chimpanzee subjects pass. In fact, chimpanzee subjects that passed the test (to recognize themselves in a mirror), also possessed a more right lateralised fronto-parietal projection, exactly as in humans during tool-making learning (Hecht et al., 2015; 2017; Stout et al., 2015; Stout and Hecht, 2017). This rightward asymmetry of connectivity could be related to a human-like rightward asymmetry initially found for the Planum Parietale in apes (Gannon et al., 2005), a finding which was replicated in chimpanzees particularly in females in relation to handedness (Taglialatela et al., 2007). Future studies in nonhuman primates should continue investigating potential links in lateralisation of the Inferior Parietal Lobe and the behaviour. It would help clarifying whether left or right lateralised brain circuits for tool-use paved the way for language brain circuits.

The Central Sulcus (CS)

The Central Sulcus (CS) is a major landmark in the brain, dividing the parietal from the frontal lobe and is one of the primary sulci developed in the brain (Chi et al., 1977). It also divides the primary motor cortex from the primary somatosensory cortex, where topographic sensory and motor representations of human body parts are organized (Penfield and Boldrey, 1937). Within this topographic organisation, a morphological landmark of hand and finger representations has been documented across the dorsal-ventral plane of the CS, known as KNOB or motor hand area, which has an omega-like shape (Yousry et al., 1997).

Regardless of the hand, the direction of handedness was found associated with contralateral asymmetries of the motor hand area (e.g., humans: Amunts et al., 1996; 2000; Cykowski et al., 2008, Sun et al., 2012). In fact, the portion of the CS that delimits the motor hand area was found deeper in the hemisphere contralateral to the preferred hand of the subjects (eg. Amunts, 2000). This feature seems however not to be related with language lateralisation. In fact, it has recently been demonstrated that the neural substrates of typical handedness measures and language brain organisation might be not related but rather independent from each other (Groen et al., 2013; Ocklenburg et al., 2014; Häberling et al., 2016).

Within an evolutionary framework, hemispheric specialisation and handedness have been historically considered unique to human language evolution (Crow, 2004; Warren, 1980). However, many primates, such as baboons or chimpanzees, also present right-handed dominance for manipulative actions, and even stronger right-handed dominance for communicative gestures (Meguerditchian et al., 2013). Just as in humans, the nonhuman
primates’, direction of handedness for object manipulation was found associated to contralateral asymmetries of the motor hand area within the Central Sulcus (Chimpanzees: Hopkins and Cantalupo, 2004; Dadda et al., 2008; Baboons: Margiotoudi et al., 2019; Capuchin monkeys: Phillips and Sherwood, 2005; Squirrel monkeys: Nudo et al, 1992). It is notable that the contralateral hand area effect in the CS was found for manipulative actions exclusively (Margiotoudi et al., 2019) but not for communicative gesture handedness. As mentioned in the previous section, handedness for gestural communication was exclusively found related to Broca’s homologue (Becker et al., 2021b), suggesting a potential independent neural substrate of handedness and language organisation in evolution. Preliminary results in juvenile baboons reported a similar neuroanatomical manifestation of early handedness, highlighting that structural asymmetries in the Central Sulcus appear early in development with the emergence of handedness behaviour (Bouziane et al., 2021). Interestingly, the motor hand area of the Central Sulcus was also shown to be related to more complex hierarchical organisation of behaviours as it was related to tool-use handedness in chimpanzees (Hopkins et al., 2017).

**Conclusion**

In this review, within an evolutionary framework across primates, we compared data about the structural inter-hemispheric asymmetries of most key brain structures that are well known to be associated with hemispheric specialisation for language processing in humans. The results of this comparative neuroanatomical approach conducted between humans and mostly chimpanzees and to a lesser extent baboons are quite straightforward and challenge the historical view that hemispheric specialisation is a human specific feature of language evolution (Crow, 2004; Warren, 1980). It becomes clear that we share the structural lateralised patterns for most language-related regions with other primate species, and even new-born monkeys, especially for perisylvian regions including the Planum Temporale and Broca’s area (Gannon et al., 1998; Catalupo & Hopkins, 2001; Hopkins & Nir, 2010; Marie et al., 2018; Becker et al., 2021c,d). Although less documented in comparison to those two historical lateralised perisylvian regions, there is some evidence that other important regions of interest within the large human language network might share the same hemispheric structural lateralisation across primate species. According to rare recent comparative results, mostly conducted in chimpanzees and to a lesser extend in baboons, those shared features includes the leftward lateralised white matter connectivity tract between Broca’s area and the Planum
Temporale - the Arcuate fasciculus (Rilling et al., 2012), leftward parietal operculum, rightward Planum Parietale and fronto-parietal projection (Gilissen and Hopkins, 2003; Gannon et al., 2005; Taglialatela et al., 2007), the rightward posterior section of the STS (Meguerditchian et al., 2016, 2021) as well as the presence of paracingulate sulcus in the left hemisphere (Hopkins et al., 2021). These collective findings suggest an important shared biological ancestral encoding between Old world monkeys, great apes and humans of what have initially been considered as neuroanatomical landmarks of brain lateralisation for language. Their presence in non-linguistic primate species clearly states that these landmarks are not human- or language-specific.

Nevertheless, it remains unclear for which shared “domain general” cognitive function between human and nonhuman primate species, that is also at the heart of language processing in modern humans, these structural hemispheric asymmetry patterns are related to and have evolved. While reviewing the nonhuman primate literature that reported clear links between anatomical asymmetries for language area homologues and hand preferences for tool-use or for gestural communication (e.g., Hopkins and Nir, 2010; Meguerditchian et al., 2012; Hopkins et al., 2019; Becker et al. 2021b), some functional roads become plausible. For instance, it is thus not excluded that both “syntactic” hierarchical sequential processing (such as the one involved in tool making and use in great apes), and the intentional communication properties (shared with the communicative gestural system in primates) might thus constitute functional candidate to have paved the way for such brain asymmetric organisation within the evolutionary framework of human language. We demonstrate therefore, that nonhuman primates such as chimpanzees, and even more phylogenetic distant species such as baboons among the Old world monkeys, offer compelling comparative models for the evolution of human brains and behaviours. In particular, a sulci and region-of-interest approach seems fruitful for comparing brain structures. In the same vein, handedness measurements for different behaviours seems fruitful for linking the laterised brain anatomy to laterised behaviours. Interesting future work could now lay in transposing this handedness knowledge to humans, to clarify for example, whether communicative gesture handedness might be a marker for language lateralisation.

Regarding specifically language evolution, we hypothesise that asymmetries for language areas may not have initially evolved for language, if language is seen as one cognitive module. Rather, each asymmetry could have evolved independently for independent cognitive functions, to adapt to unknown environmental pressures. This could explain the unclear relationship between structural and functional asymmetries related to language areas. The
structural asymmetry would here be a more ancient fossil of other cognitive specialisation on which the functional language asymmetry got piggybacked. The functional and structural specialisation of these structures may next have been important nests for developing intentional communicative behaviour in nonhuman primates, which later evolved to language processing in our species. In other words, “perisylvian language asymmetries” are not specific to language but could rather be exaptations of pre-existing specialisations for other cognitive functions, which together make up what we call “language”. Therefore, “domain general” language-related brain architecture associated with intentional communicative or syntactic behaviours might rather be shared between humans, apes and at least baboons of the Old world monkey family. Such an asymmetric brain organisation might have thus emerged from their common ancestor around 25 million years ago and later increased during hominin evolution.

**Author Contribution**
Conceptualization, Y.B. and A.M.; writing—original draft preparation, Y.B.; writing—review and editing, Y.B. and A.M.; supervision, A.M.; project administration, A.M.; funding acquisition, A.M. All authors have read and agreed to the published version of the manuscript.

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**Conflict of Interest**
The authors declare no conflict of interest.

**Reference**


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