nccr evolving language
NATIONAL CENTRE OF COMPETENCE IN RESEARCH

Progress Report – Year 5

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Executive summary

In Phase 1 we discovered ever more cognitive precursors and parallels of language in animals and ever fewer architectural parallels in artificial systems. We have now begun to identify evolutionary trajectories along all four Tinbergian dimensions and to explore novel ways of bridging between neural and artificial systems in terms of modelling and clinical applications. Capitalizing on the tight interdisciplinary integration of our consortium we re-structured the problem of language along its natural dimensions in syntax and meaning and highlighted the continued evolution of languages as one of its most specific traits (acquisition, diversification) and the interactional setting of language as one of the core conditions for processing and learning, and as an ecological driver of its evolution.

The past year has seen the publication of many key results of Phase 1 work (see Appendix 0). Phase 2 work has focused on bringing a new generation of students and researchers into the consortium and developing protocols for their specific tasks; therefore, most progress has been on the conceptual and methodological side. Some highlights include new ways of leveraging genetics for understanding the isolation vs contact dynamics in linguistic evolution; a novel approach to systematically compare hierarchy and its encoding in brain across language, animal communication, and action; a move to examining the cognitive roots of language through event and event sequences in addition to objects and referents; a move outside the classical language network research to better understand the evolutionarily distinct components that made processing and learning possible in language; and new approaches to leverage deep learning models to find optimal anchors for network activation in aphasia.

In terms of structure-related areas, our initiatives seek to actively involve the community in a wide range of activities, aiming to promote positive change beyond the initiative of our office. Over the past year, two measures stand out for their particularly strong impact. First, recognizing that media coverage often favours research published in a few high-impact journals – and that, as a result, many researchers choose not to engage with the broader public in a significant portion of their work – we have developed an easy process to encourage our researchers to proactively increase the visibility of all outputs aligned with the NCCR's vision. By showing our researchers that their work resonates with society (and vice-versa), we not only highlight the value of their contributions but also, hopefully, inspire them to engage more actively with the broader public. Second, we are expanding our educational outreach in socio-economically disadvantaged countries by encouraging our early-career researchers to organize and participate in workshops, in collaboration with partner universities. This initiative not only broadens their professional experience but also provides a meaningful opportunity to share their expertise with new audiences.

In terms of structural measures, the most relevant change has been the enlargement from two to three home institutions, with UniNE joining with two new professorships in behavioural physiology and psychology (planned) and a new research infrastructure, the 'Comparative Intelligence Research Infrastructure' (CIRI). The two existing home institutions have continued to invest and change the research landscape with new professorships in the key disciplines (UZH: linguistics, anthropology, genetics; UNIGE: computational linguistics, genetics/computational neuroscience).

Results from Year 5: Highlights and output

Since the last Progress Report, a considerable amount of Phase 1 research has been published. A list can be found in the Appendix.

1.1.1 Project Diversification

The Diversification Project probes the emergence of dynamics in language, i.e., what drives linguistic evolution; (Bickel, Giraud, Zuberbühler & Van Schaik 2024; Cerrito et al. 2025) (WP Stationarity), why this happens (WP Diversity Functions) and what the underlying mechanisms are (WP Diversity Conditions).

WP Stationarity

PIs: Burkart, Manser, Stadler, Zuberbühler, Bickel, Hahnloser, Oliveira, Townsend, ***Migliano***[1]*, Shimizu, Furrer ; Collaborating PIs: Widmer; Senior Researchers: Vaughan, Barbieri, Cathcart; Staff: Montello, Perrier, Graff, Jud, Quilodrán Venegas, Ciuffi, Dees, Jing, Neureiter, Takahashi ; Associate Investigator: Van de Waal ; Senior Advisor: Van Schaik*

Our review work suggests that the ergodic, and hence stationary, nature of linguistic evolution is likely to have evolved in response to social needs for linguistic signalling of social boundaries and cohesion, i.e., ethnic marking (Bickel, Giraud, Zuberbühler & Van Schaik 2024; Cerrito et al. 2025; Stoll et al. 2025) (see **Figure 1**). Ergodic evolution makes this possible because it guarantees variation without expanding the space of what can be learned and processed. To explore to what extent such a process might have precursors or parallels in other animals (**CallDynamics Task**), we collaborate with TTF Datascience in developing VoCallBase (see Section 1.1.6) and are intensively processing vocalization data across many mammalian and bird orders. At the time of writing, we have 20 datasets in various stages, coded for a larger range of socio-ecological predictors of diversification. A case study (yet unpublished) of titi monkey (*Callicebus nigrifrons*) vocalizations suggests that acoustic group differences are more pronounced at the end of a call sequence than at the beginning. This is consistent with greater variation during the "let-down Phase" of chimpanzee pant-hoot sequences (Soldati et al. 2025) and with more suffix than prefix evolution in language (Bybee, Pagliuca & Perkins 1990; Cysouw 2009; Himmelmann 2014). We are currently working on assessing these patterns at larger scale, and we explore them in conjunction with modelling work in WP Diversity Condition (Task Diversity Generation) on the differential role that initial and later elements have on probabilities of change.

[1] Names shown in **bold** are the WP coordinators, who should be contacted in case of questions or requests for further information.

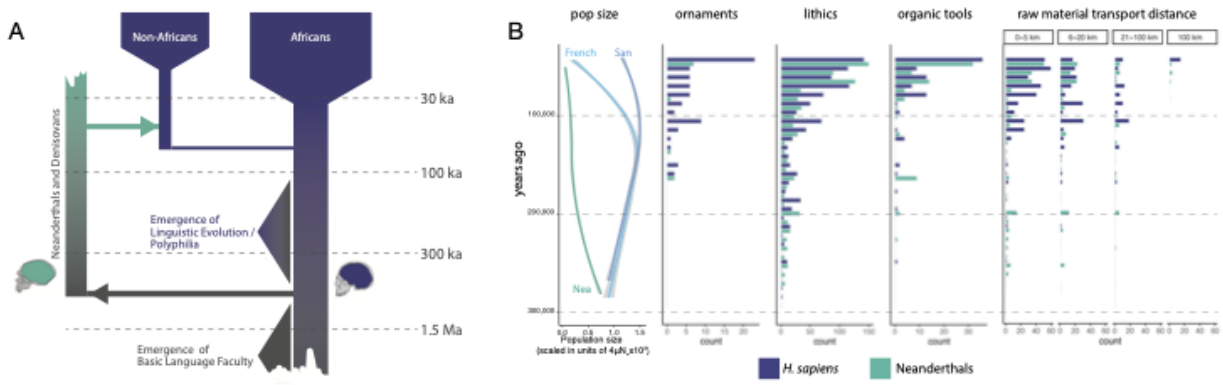


Figure 1. A) Ergodic evolution emerged in response to polyphilia, **B)** an urge to diversify and distinctly mark ethnic groups that was triggered by growing populations and was co-indexed by increasing diversity in ornaments and population connectivity (Cerrito et al. 2025). It is an unresolved question whether such transitions have precursors or parallels elsewhere in animals.

We have also made progress in understanding the socio-ecological drivers of linguistic evolution (**Population History Task**). We first continued our work on language speciation in response to demography estimated from population genetics (Barbieri et al. 2022). A first study (unpublished) used skyline plots (Stadler et al. 2013) to identify shifts in speciation rates in Indo-European that likely point to demographic turnovers; we are now following up on this by building in historically evolving predictors (cf. below). Second, we confirmed the impact of demographic history, as inferred from population genetics, on the distribution of individual language features (Matsumae et al. 2021; Padilla-Iglesias et al. 2024) at a global scale (Graff, Ringen, et al. 2024), leveraging databases that we curated for feature independence (Graff et al. 2025). Based on this, we now explore more deeply distributions under genetic isolation as these might better mirror evolutionary dynamics before the Neolithic intensification of population contact. In parallel, we work on how different subsistence styles and waves of migration have affected structural diversity, contrasting for example seafaring and agricultural populations in insular Southeast Asia. In this work we pay particular attention to the differences between the evolution of languages and the evolution of other behaviours (Bickel, Giraud, Zuberbühler & Van Schaik 2024), a difference that we recently confirmed with regard to music (Passmore et al. 2024) and musical instruments (Padilla-Iglesias et al. 2024).

On the methodological side (**Phylogenetic Modelling Task**), we build on regression-inspired approaches to phylogenetics (Lemey et al. 2014; Cathcart & Bickel 2025) to develop a more flexible framework that allows various predictors (static or evolving, discrete or continuous) to drive parameters of evolution, such as birth and death rates, trait substitution rates, or attraction optima. We are currently validating methods that integrate this approach with phylodynamic models that allow sampling/survival uncertainty (Stadler et al. 2013; Kühnert et al. 2016) in order to track how the evolution of diversification rates across geographical regions. In parallel, we have reparametrized Continuous-Time Markov models in terms of global speed and stationary probabilities (Cathcart & Bickel 2025) to more closely align estimands with the focal terms of linguistic evolution (Bickel, Giraud, Zuberbühler & Van Schaik 2024).

WP Diversity Functions

*PIs: **Bangerter**, Burkart, Clément, Mansfield, Manser, Mazzarella, Oliveira, Stadler, Townsend, Widmer, Zuberbühler; Collaborating PIs: Bickel, Migliano, Shimizu; Senior Researchers: Barbieri, Cathcart, Vaughan; Staff: Brügger, Ciuffi, Le Fur, Roberts, Schindler; Associate Investigator: van de Waal; Senior Advisor: Van Schaik*

Work on contact events in WP Stationarity revealed only few direct signals of schismogenesis from grammar but strong overall limitations on structural borrowing, robust over diverse demographic conditions (see **Figure 2**)(Graff, Blasi, et al. 2024). This suggests ethnic marking is more tied to entire languages as they speciate over time, chiefly measured by lexical replacements, and less tied to specific structural features. Focusing therefore on speciation rates and leveraging new phylogenetic modelling tools (Douglas et al. 2024), we found (in as yet unpublished work) bursts to be driven by awareness of group differences, as measured by travel distance and adjusted for population size and prestige (**Schismogenesis Task; Figure 2**), consistent with our dialect-level (Mansfield, Leslie-O'Neill & Li 2023) and phylogeographic (Cathcart & Bickel 2025) results. This notwithstanding, we continue probing individual features for their schismogenetic impact, in particular in phonology where we have observed the strongest signals so far (Graff, Blasi, et al. 2024; Cathcart & Bickel 2025).

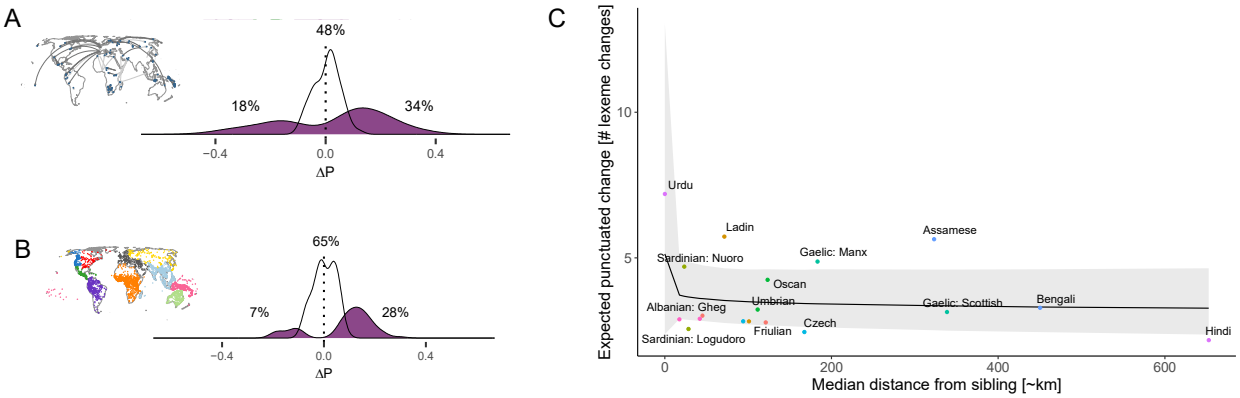


Figure 2. A-B) Probabilities of sharing feature states are more often higher, not lower, than random baseline expectations, suggesting less schismogenesis and more borrowing in structural features under genetic (**A**) and areal (**B**) contact between pairs of languages (Graff, Blasi, et al. 2024). **C)** By contrast, lexical replacement bursts reflect schismogenesis as their size decreases with travel distance between a language and its sibling, marginalising out language area size (a proxy for population size) and literary prestige. (Some sibling labels removed from the graph for visibility. Ongoing work by Roberts et al.)

Moving beyond structures and word/call repertoires, we explore the role of usage patterns in driving diversification and cohesion, starting in interpersonal synchrony (in conjunction with TTF Instrumentation and WP Information Integration). In the **Story-Telling Task** we designed an experiment measuring effects of storytelling on these outcomes that we will conduct in three maximally diverse languages: Swiss German, Shipibo-Konibo (Peru) and Mum (Papua New Guinea). The experiment is under way in Swiss German with data collection across the Bern-Mittelland region. Fieldwork in Papua New Guinea and Peru is currently being prepared.

To trace the evolutionary roots of diversification functions, we furthermore probe evidence for social and linguistic norms in nonhuman primates (**Protonormativity task**). First, we identified group differences in combinatorial repertoires as an initial step toward understanding proto-linguistic norms in chimpanzees. Since captive populations exhibit both intra- and inter-group genetic variation, they represent the ideal testbed for culturally driven differences in communicative behaviour. We use existing data from a chimpanzee group housed in Sigean Zoo in France and will add data from the largest captive chimpanzee group in Switzerland (Gossau Zoo). Second, we build on recent (yet unpublished) work suggesting that marmosets "protest" (by giving *tsik*-vocalisations) when their close bond partner in a dyadic interaction diverges instead of converges to their call. To investigate whether this reflects a normative expectation, we will expose a third-party listener to converging vs diverging dyadic

interactions. We will measure their reaction to this putative norm violation with looking times and thermography and evaluate which individual they prefer to subsequently interact with via a choice test.

WP Diversity Conditions

*PIs: **Bavelier**, Berthele, Bickel, Brem, Giraud, Golestani, Guggisberg, Meyer; Collaborating PIs: Hervais-Adelman, Laganaro; Senior Researchers: Cathcart, Olasagasti; Staff: Balboni, Ghambaryan, Giglio, Haugg, Kepinska, Maghsadhagh, Marchesotti, Rampinini, Turker, Urwicz, Wombacher; Associate Investigator: Preisig*

To unravel the neurobiological mechanisms that enable linguistic evolution, we have started to develop a model of how the brain decides on deviating from norms (**Diversity Generation Task**). We capitalize on neurocomputational models of decision making in action that focus on how new options are weighted against existing ones through mixture models and are then chosen based on intrinsic and social reward functions (Domenech, Rheims & Koechlin 2020; Collins & Koechlin 2012). We are currently exploring how to integrate the specific challenges of language as opposed to action, notably the fact that language production needs to carefully integrate the atemporal hierarchy of compositional structures with temporal sequencing for production. Concurrently we are preparing cross-linguistic experiments on differential freedom of choice during sentence planning, linked to related interests emerging in the Call Dynamics Task (WP Stationarity).

Further insight into the neural substrates of linguistic evolution comes from processes that require similar flexibility and rapid adaptations to change in verbal behaviour. In the **Aptitude Task** we focus on bilingual language control as one such process. Our previous work (Rampinini et al. 2025) identified high vs low language aptitude, correlated with performance in domain-general cognitive skills (Rampinini et al. 2024) and mirrored by functional and structural differences in the left inferior frontal and parietal cortices, areas we found to explain significant variance in functional brain data across a variety of language tasks, including story listening, as well as in a variety cognitive tasks (Balboni, Rampinini, et al. 2025). The left inferior parietal cortex has also been implicated in language talent and shown to be malleable in the case of multilingualism (Della Rosa et al. 2013; García-Pentón et al. 2014; Kepinska et al. 2023; Mechelli et al. 2004; Pötzl 1925), even though language aptitude does not always cluster with high levels of multilingualism, at least in individuals who are less likely to be elective multilinguals (Rampinini et al. 2024). This may arise from bilingualism also relying on domain-general skills, such as episodic memory in line with changes in the anatomy of a hippocampal subregion (Golshani et al. 2024a).

We also expect people who cluster high on measures of reading and reading mediators to show differences in the anatomy (volume, but also shape) of auditory regions, as shown in the context of language aptitude and of dyslexia (Blockmans et al. 2023; Kepinska et al. 2024; Ramoser et al. 2024b) using our auditory cortex toolbox (Dalboni da Rocha et al. 2023).

Concurrently, genetic profiling of our participants' data is proceeding thanks to our collaborators at the MPI Nijmegen. We are extracting polygenic risk scores for language, dyslexia and for musical beat. These will further inform our subgroup classification by documenting links between genetic marker and brain and behavioural measures. One prediction is that those individuals in our sample who show high language giftedness will show polygenic profiles corresponding to better performance on a subset of language tasks that have been benchmarked in up to 34,000 people (Eising et al. 2022). Furthermore, we now leverage our Phase 1 results to explore similarities and differences between people with good knowledge of an increasingly high numbers of languages, probing possible differences in reward areas.

In a third line of research (**Neuromodulation Task**), we approach the neural substrates of linguistic evolution through the neuroplasticity for language learning, thereby also contributing to clinical

questions of how to restore language functions. Phase 1 results showed that modulating network interactions is much more effective in enhancing language functions than individual brain regions (Farcy et al. 2024; Haugg et al. 2023). We are now systematically comparing different neurostimulation techniques to evaluate their effectiveness in modulating interactions within language networks. In an on-going randomized study in healthy participants, comparing the stimulation of the left inferior frontal gyrus while learning new words, we are collecting evidence that high-density transcranial random noise stimulation (HD-tRNS) is more effective than transcranial alternating current stimulation (tACS) or sham stimulation. Of interest, tRNS may thus act in a rather domain-general manner enhancing the rate of evidence accumulation in the network targeted (Groen et al. 2018).

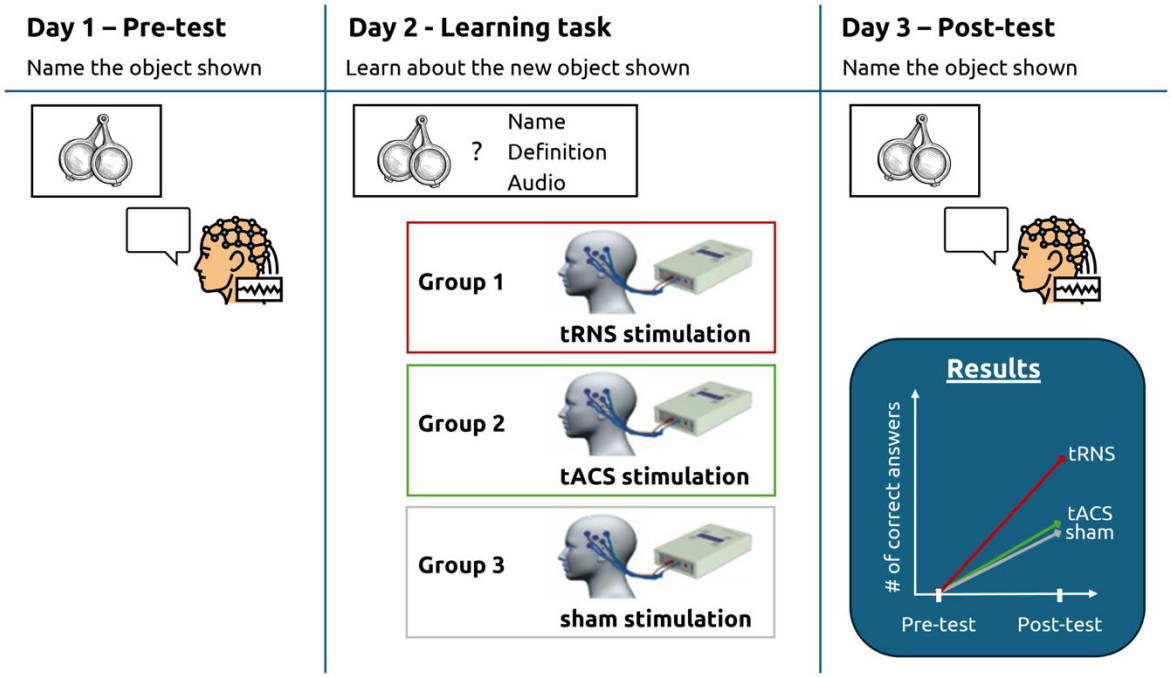


Figure 3. Enhancing new-word learning through neuromodulation. Healthy participants completed a picture-naming task involving rare nouns and verbs during a pre-test (Day 1) and post-test (Day 3). On Day 2, they underwent a learning session in which the target words were trained alongside non-invasive brain stimulation targeting the left inferior frontal gyrus. Participants were randomly assigned to one of three stimulation conditions: transcranial random noise stimulation (tRNS), transcranial alternating current stimulation (tACS) at 4 Hz, or sham stimulation. Preliminary findings indicate that tRNS enhances new-word acquisition compared to tACS and sham stimulation.

Table 3. Output for Diversification Project.

TASK	REFERENCE	OA	PID
APTITUDE	(Balboni, Kepinska, et al. 2025)	preprint	osf
APTITUDE	(Mohammed et al. 2025)	yes	openneuro
APTITUDE	(Balboni, Rampinini, et al. 2025)	preprint	OSF
APTITUDE	(Ramoser et al. 2024a)	yes	Upon request
APTITUDE	(Golshani et al. 2024b)	yes	Upon request
APTITUDE	(Kepinska et al. 2024)	preprint	-

PHYLOGENETIC MODELLING	(Craevschi, Babinski & Cathcart 2025)	preprint	gitlab
PHYLOGENETIC MODELLING	(Herce & Bickel 2025)	yes	gitlab
PHYLOGENETIC MODELLING	(Graff, Lischka, et al. 2024)	yes	github
PHYLOGENETIC MODELLING	(Cathcart & Bickel 2024)	yes	No data associated
POPULATION HISTORY	(Okada & Shimizu 2024)	yes	Data gathered from other studies
POPULATION HISTORY	(Padilla-Iglesias et al. 2024)	yes	github
SCHISMOGENESIS	(Graff, Ringen, et al. 2024)	preprint	-
SCHISMOGENESIS	(Graff, Blasi, et al. 2024)	preprint	-
SCHISMOGENESIS	(Ebert, Bickel & Widmer 2024)	yes	Data gathered from other studies

1.1.2 Project Acquisition

Project Acquisition seeks to document the mechanisms by which not only social, cognitive and emotional skills of the learner, but also social context and the nature of the interactions shape the development of communicative behaviours (WP Pattern Production). Here, one of our special foci is on turn-taking given its conserved status through evolution and key role in supporting communication during development. We leverage digital technologies to better characterize the range of possible developmental trajectories subtending language acquisition and its neural bases, as well as to develop novel digital tools, such as video games to assess, intervene and enhance language learning (WP Learning Trajectories).

WP Pattern Production

*PIs: Burkart, Hahnloser, Kazanina, Schaer, **Stoll**; Collaborating PIs: Bavelier, Bshary; Staff: Akahoshi, Basha, Dickerman, Ilaridou, Junker, Kreiliger, Rüst, Wang; Senior Advisor: Van Schaik*

One notable feature of child-directed speech is pitch. To better understand its role, we focus on how variations in pitch affect attention, and ultimately language learning, in both children with autism spectrum disorder (ASD) and neurotypical (NT) children. We build on previous work on preschoolers in the Geneva Autism Cohort (Wang et al. 2023; Wang et al. 2025), employing EEG and eye-tracking while the children watched a cartoon. We investigate neural tracking of pitch in both populations, considering the diverse language profiles present in ASD children. Repetitions have been identified in Phase 1 as a possible universal structural feature of the input in human child-directed speech and other species engaging in tutoring (Lester et al. 2022; Schick et al. 2022). Repetitions of words in quick succession can help infants and toddlers in word learning (Brodsky & Waterfall 2007; Schwab & Lew-Williams 2016; Slone et al. 2023). Available dispersion measures (Gries 2022; Wojcik & Goulding 2025) either strongly correlate with frequency or are sensitive to truncation of the observation window (Goh & Barabási 2008; Schwab & Dellwo 2021; Slone et al. 2023). To study the temporal distribution of repetitions in the **Input Features Task**, we developed a new measure of burstiness that addresses limitations in existing approaches based on temporal clustering (Goh & Barabási 2008). Preliminary results indicate significant differences in burstiness between child-directed speech and adult language, and between written and spoken

modalities. Repetitions are spaced further apart in written text, occur more closely in spoken language, and are closest in child-directed speech. This is in line with the dense repetition in children's input supporting language learning (Schwab & Lew-Williams 2016; Vlach & Johnson 2013).

In the **Tutoring Task** we assess the role of tutoring for the acquisition process in humans and a vocal learner animal, the zebra finch, with a focus on input features, such as repetitions and pitch. We have developed a robust method for assessing acoustic similarity in zebra finch syllables and are currently extending this to human vocal data. A cross-linguistic study assessing the role of acoustic and structural features has yielded initial evidence that both short- and long-term adult accommodation to children significantly influence structural and acoustic aspects of language acquisition. We are now designing an experiment to examine how acoustic and structural features of vocal directedness (undirected / female-directed / juvenile-directed) affect vocal imitation in zebra finch juveniles.

Conceptually, the evolution of vocal learning has long been a conundrum. On the one hand, parallels in vocal learning across species suggest similarities in the neurobiological mechanisms, possibly even deep homologies (Scharff & Petri 2011). On the other hand, the functions of vocal learning seem strikingly diverse, the work of convergent evolution. A survey across birds and mammals shows that the most common functions among animals are in mate attraction and parent-offspring recognition, both absent in human speech (Stoll et al. 2025). At the same time, nonhuman primates show vocal accommodation, a weak version of vocal learning, in the service of social boundary marking and cooperation. This suggests that human vocal learning evolved from accommodation as a form of vocal homophily (**Figure 4**).

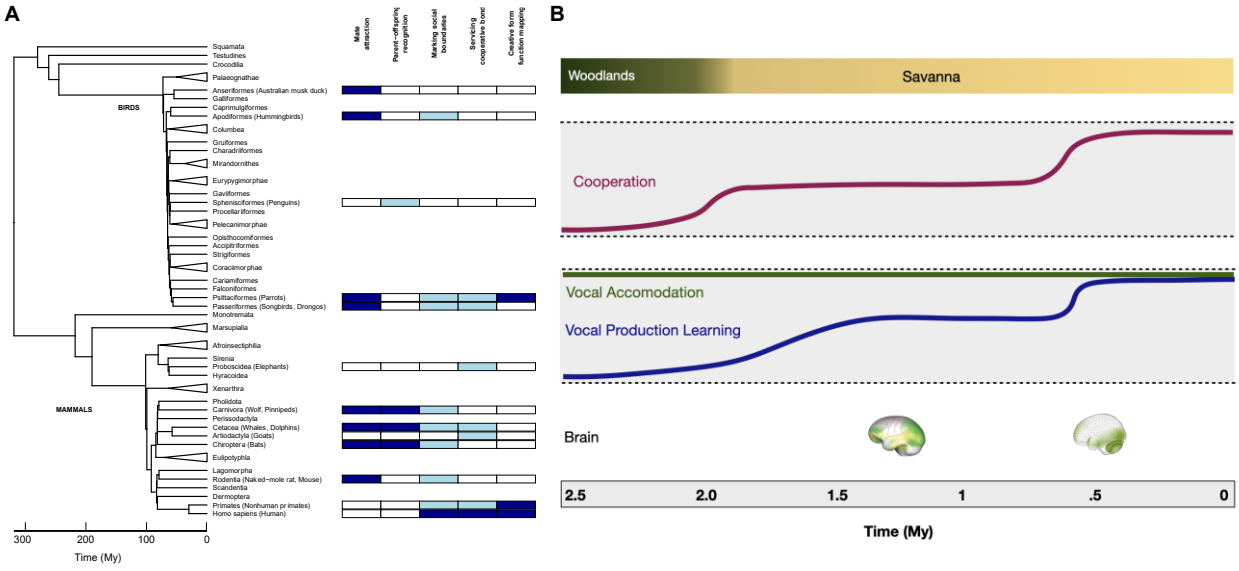


Figure 4. A) Distributions of two main kinds of vocal learning (vocal production learning, in dark blue, and vocal accommodation, in light blue) suggest striking variation in function. (Tip taxa are orders, but where vocal learning is recorded for isolated taxa within orders, these are mentioned after the order.) **B)** Primates differ in restricting accommodation to social functions, suggesting the human variant was evolutionarily driven by the intensified cooperation required after they entered the savanna 2My ago and in turn selected for brain changes in two major steps, one before (Ponce de León et al. 2021) and one after (Gunz et al. 2019; Cerrito et al. 2025) the split from Neanderthals (Stoll et al. 2025).

WP Learning Trajectories

*PIs: Attout, Barthele, Bavelier, **Brem**, Golestani; Collaborating PIs: Giroud, Giraud, Magimal-Doss; Staff: Aras, Bochud, Damas Riontino, Karipidis, Klotz, Schreiber; Associate Investigator: Pasqualotto*

Language learning extends well beyond the early years with increasingly more complex and richer speech comprehension during later childhood. However, children's language and literacy development—particularly in multilingual learners – is highly variable. Our aim is to better characterise this variation, towards more effective intervention in tune with different learning trajectories. The overall goals of this WP are to (i) establish early, reliable predictors of reading impairments, (ii) better understand individual differences in brain network development—especially in children with diverse multilingual linguistic experience—and (iii) support reading development through personalized, gamified training.

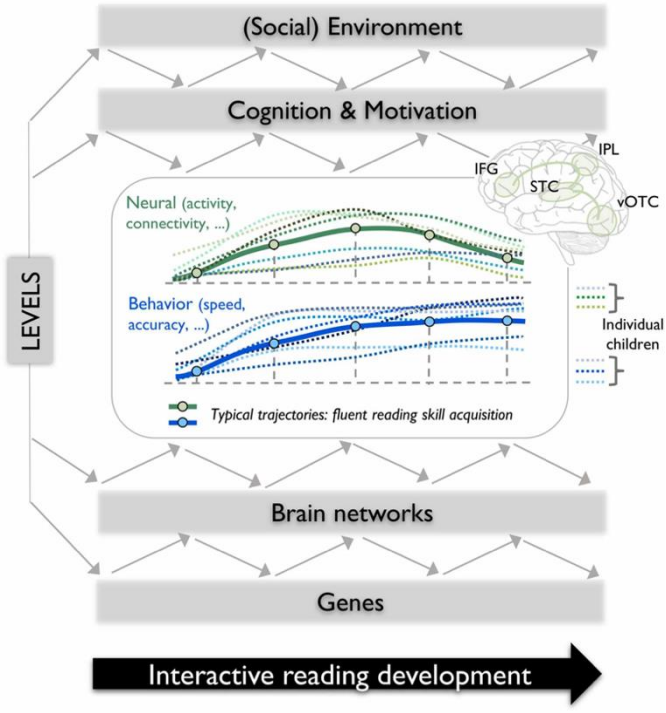


Figure 5. Schematic illustration of children's individually variable neural and behavioural reading trajectories. Multiple interactive levels (genes, brain networks, cognition, motivation, and social environment) dynamically shape children's idiosyncratic trajectories of reading development (from(Bonte & Brem 2024)).

In the **Behavioural Trajectory Task**, we are building on our previous research, which combined brain imaging and computational modelling, showing that children with poor reading skills exhibited both deficient letter-speech sound learning and altered connectivity in the associated brain networks (Frei et al. 2025), which may hinder the formation of robust letter-speech sound representations and, in turn, impair their use during reading. Furthermore, we also showed altered structural covariance patterns in brain regions involved in reading—suggesting atypical network-level development in school children with dyslexia (Haugg et al. 2025), as well as disruptions in letter-speech sound correspondence learning as mentioned above. These results have opened new avenues for targeted neural intervention, such as neurofeedback (Haugg et al. 2023) or neurostimulation (see WP Diversity Conditions), which aim to strengthen the function of affected networks. We now aim to improve screening for early prediction of

literacy outcomes in multilingual pre-readers by first developing and validating dynamic, language-neutral screening tools designed to overcome the limitations of traditional static assessments (Bonte & Brem 2024). These include a rapid object naming task using cognate words, rhyme and phoneme identification tasks, and a dynamic letter-speech sound learning task. These novel tools will enable more precise early identification of children at risk for reading difficulties, particularly those from multilingual backgrounds who are often underrepresented in current research.

In the **Neural Genetics Trajectories Task,** we seek to improve screening for early prediction of literacy outcomes in multilingual pre-readers, by documenting how diverse language experiences shape brain development in relation to reading acquisition. We are currently designing and piloting neuroimaging tasks to study alterations in brain structure, function, and connectivity during child development. While research on reading and language development has made significant strides in recent years, studies have often focused on monolingual children) (Bialystok 2007; Bonte & Brem 2024). In response, we are currently developing neuroimaging paradigms to study how multilingualism shapes the development of language and reading networks in the brain, providing insights into developmental trajectories in children with diverse linguistic backgrounds. These paradigms include an audiovisual cognitive flexibility task, an audiovisual correspondence learning task, and three complementary functional localizer tasks (visual, auditory, and audiovisual), which will help identify core nodes within the brain's reading and language networks. This work, along with the published structural covariance results (Haugg et al. 2025), will be complemented by the work in the Diversity Conditions WP.

In the **Digital Intervention Task**, finally, we follow up from promising Phase 1 findings on text reading fluency in children aged 7–9 after exposure to a videogame, 'Legends of Hoa'manu' (LoH) (Pasqualotto 2025; Pasqualotto et al. 2022). LoH is a game-based intervention designed to enhance attentional control and executive functions, which are foundational for reading acquisition. A core innovation is a dynamic difficulty-adjustment algorithm, which personalises the experience in real time both in terms of activities and in terms of dimensions (e.g., speed, duration, number of items), ensuring highly personalized learning trajectories, while keeping the experience variable enough to ensure skill transfer to new tasks (Pasqualotto et al. under review). In future work, we will expand to multi-domain approaches (Pasqualotto et al. In prep.), targeting not just cognition and language (Pasqualotto et al., 2022) (Mehringer et al. 2020), but also auditory processing and audio-visual learning, which are often deficient in dyslexia (Marchesotti et al. 2020) (Pasqualotto et al. submitted).

Table 4. Output for Acquisition Project.

TASK	REFERENCE	OA	PID
INPUT FEATURES	(Wang et al. 2025)	yes	-
TUTORING	(Zai et al. 2025)	preprint	-
DIGITAL INTERVENTION	(Pasqualotto et al. 2025)	preprint	osf

1.1.3 Project Syntax

Humans interact by transforming mentally held representations of events into linear streams of sounds, which are then back translated by listeners, usually into the same mental representations. This is possible because both speakers and listeners represent events with shared hierarchical structures, the cognitive foundations of syntax. Our Phase 1 research has shown that great apes likely perceive real-world events in human-like ways, which makes it even more puzzling that they never seem to report on their

perceptions. Possibly this is because their mental representations lack hierarchical depth, or possibly because they lack sufficient vocal control to express them. Project Syntax is set out to understand how evolution has shaped the cognition of syntax, tightly integrating linguistic, comparative, neurobiological and computational approaches. It interacts closely with the Meaning Project by asking how mental content and its linguistic representation is mapped to articulated expressions in production and comprehension. Our working hypothesis is that, unlike meaning, syntax is fundamentally about time - vocal expressions emerge from interactions between different timescales by which hierarchically structured meaning becomes regimented into a one-dimensional speech stream. Three work packages - WP Events, WP Locality, WP Hierarchy – tackle the problem, each equipped with a unique portfolio of methods harvested from different disciplines, including animal behaviour, neurobiology, computational science and linguistics.

WP Events

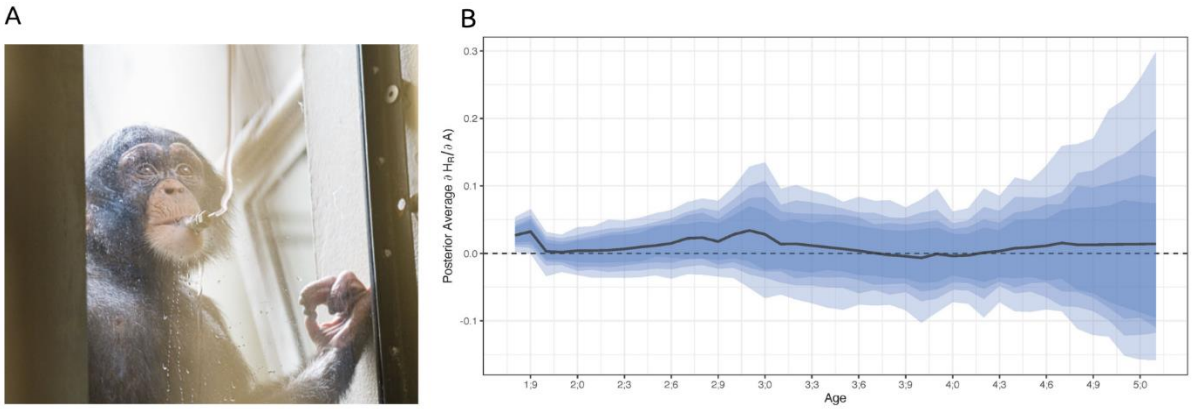
*PIs: Bickel, Daum, Mansfield, Stoll, **Zuberbühler**; Collaborating PIs: Giraud, Townsend; Staff: Brocard, De Becker, Herce, Hong, Koopman ; Senior researchers: Cathcart, Schnell, Wirobski*

WP Events is to elucidate the arguably most profound divide between animal communication and language: that no animal conveys the structure of even most basic transitive events, i.e., the fact that something that acts causes something else to change. During Phase 1, we have ruled out that this inability is rooted in different kinds of event perception, since both human and non-human hominids inspected, absorbed and reasoned about transitive events in comparable ways (Brocard, Vanessa A.D. Wilson, et al. 2024; Brocard et al. 2025; Wilson et al. 2024). WP Events now investigates other possible sources, such as a cognitive inability to compute intransitive event components into transitive composites or an executive inability to externalise event representations into communicative expressions. Two teams are researching the problem.

First, the **Event Cognition Task** is in the process of designing non-linguistic tests to investigate what exactly different species of hominids (chimpanzees, bonobos, gorillas, orangutans, humans) can represent when witnessing real-world events, such as the causal nature between agent and patient links, their temporal relations, roles or individual features. A plausible hypothesis is that, at any given time, nonhuman hominids can track less content, perhaps only one participant of a transitive event (agent or patient), without being aware that the behaviour of one is the mould of the other. An eventual constraint of this nature would prevent animals from actively communicating transitive events for mere cognitive reasons. The team will develop and test hypotheses with established methodology by which events (intransitive vs transitive) are presented on computer monitors to investigate what components subjects extract and whether there are signs of integration. They will start with social interactions but will also test events characterised by factual, procedural or spatial causation to see whether any of these domains are more prone to transitive representation than others. The idea is to carefully monitor and document the even slightest communication efforts by subjects to determine which event aspects they find noteworthy and feed forward for signal externalisation. The team has secured access to great apes at different zoos in Europe (Basel, Gossau, Zurich, Edinburgh) and the U.S. (Ape Cognition and Conservation Initiative in Iowa), with some language-trained individuals.

Complementary is the **Transitivity Task** that investigates whether the apparently striking animal-human differences in 'who-does-what-to-whom' computation are possibly more gradual than categorical. Relevant is that, across languages, speakers tend to avoid densely packed utterances and instead favour delivering information in a remarkably inefficient, piecemeal fashion (Chafe 1987; Chafe 1991), suggesting, even for humans, computational constraints during production or comprehension. Although transitive meanings are ubiquitous, and languages have formal means to express them, speakers often

underexploit their options at all levels of expression. These observations open the possibility that humans share an evolutionarily older hominid bias against expressing transitive events, possibly because of computational load. Such a bias would be of further relevance as it may shape linguistic evolution in a predictable way: whatever is computationally costly is difficult-to-fake and a candidate commodity for marking group membership and social show-offs, analogous to the Handicap Principle in biological evolution (Zahavi 1975; Bickel & Zúñiga 2017). For these reasons, transitivity is also promising to study during language acquisition (are transitive structures harder to learn than intransitive ones?), production (does context determine transitive expressions across languages in similar ways?) and linguistic



phylogeny (what global tendencies are visible in transitive constructions?). Here, the team has begun to study the acquisition of agent-verb-patient transitive constructs in English-speaking children (**Figure 6**) and currently prepares cross-cultural experiments on word order in the production of fully lexicalized transitive sentences.

Figure 6. A) Chimpanzee at Basel Zoo observing a video clip with an agent-action-patient event on an eye tracking device. Comparing the eye gaze patterns between human and nonhuman apes can reveal something about the underlying shared and species-specific cognitive processes required for syntactic communication. **B)** Partial effect of age on approaching lexical flexibility in agent-verb-patient sentences with two full lexical noun phrases, adjusted for the increasing flexibility with ever-longer sentences and variation across children (H_R: relative entropy of lexical choices in agents, patients, verbs; A: Age). For English, as shown here, we find very weak effects early but, overall, these sentences do not seem to pose special cognitive difficulties. We are currently expanding this to more languages in the ACQDIV corpus.

WP Locality

*PIs: Bickel, Burkart, Golestani, Meyer, Sennrich, Stoll, **Townsend**; Collaborating PIs: Furrer, Giroud, Kazanina, Mansfield, Stadler, Zuberbühler; Staff: Howard-Spink, Li Calzi, Marcante, Mircheva, Nitschke, Soldati, Spiess, Van Boekholt, Watson; Associate Investigators: Preisig, Sauppe; Senior Advisor: Merlo*

WP Locality aims to understand the neurobiological mechanisms driving the balance between local (adjacent) vs. non-local (non-adjacent) dependencies and what pressures or forces might be guiding this in linguistic and biological evolution, above and beyond effects that we have shown to result from stochastic fluctuations in word classes (Mansfield & Krapp 2025). The WP is divided into three tasks.

First, the **Call Locality Task** is to unpack the evolutionary origins and drivers of non-local structures through investigating internal organisation of primate vocal sequences. The team uses marmosets to investigate the function of local and non-local sequences, which have been attested across call bouts in Phase 1 (Bosshard et al. 2024). To this end, the team has collected a large data set of dyadic vocal interactions, including all possible within-group dyads of 14 different groups of marmosets (>67,000

calls), with a first goal to automatise segmentation and analyses, in collaboration with TTF Data Science. This technical progress will eventually allow us to quantify sequential structure within and between call bouts and between dyads in terms of their internal hierarchical organisations.

Second, the **Locality Dynamics Task** probes similar questions but at the scale of linguistic rather than biological evolution, hereby taking a cross-linguistic approach incorporating corpora from diverse languages (e.g., English, Japanese) and speech registers (e.g., infant-directed communication). It investigates facilitatory cues for non-adjacent dependency learning (as measured by child production) in a cross-linguistic longitudinal corpus study, such as dependency length, edge effects, transitional probabilities and so forth, using the ACQDIV corpus database for English, Russian, Japanese, Turkish and Indonesian. Preliminary analyses on English suggest that non-local dependencies with shorter lengths and at least one edge token are learnt earlier than other dependencies.

Third, the **Locality Processing Task** aims to understand the neurobiological mechanisms supporting the linearisation of hierarchical non-local sequences. The team uses fMRI data collected during naturalistic listening and speech production (Chen et al. 2017; Lee, Chen & Hasson 2023) to investigate how different measures of locality are associated with brain responses across core regions of the language network (left posterior middle temporal gyrus and the partes operculares and triangulares of the left inferior frontal gyrus), regions that have undergone recent evolution (Gunz et al. 2019; Casten et al. 2025; Tajima et al. 2025; Eising et al. 2022). We extend previous work that found critical differences between production and comprehension (Giglio et al. 2024) by modelling responses over the time windows defined by the 1.5s sampling intervals of the fMRI scans. For this purpose, we convolve word-by-word metrics (such as dependency length or the number of opened/maintained/closed dependencies) with hemodynamic responses (HRF).

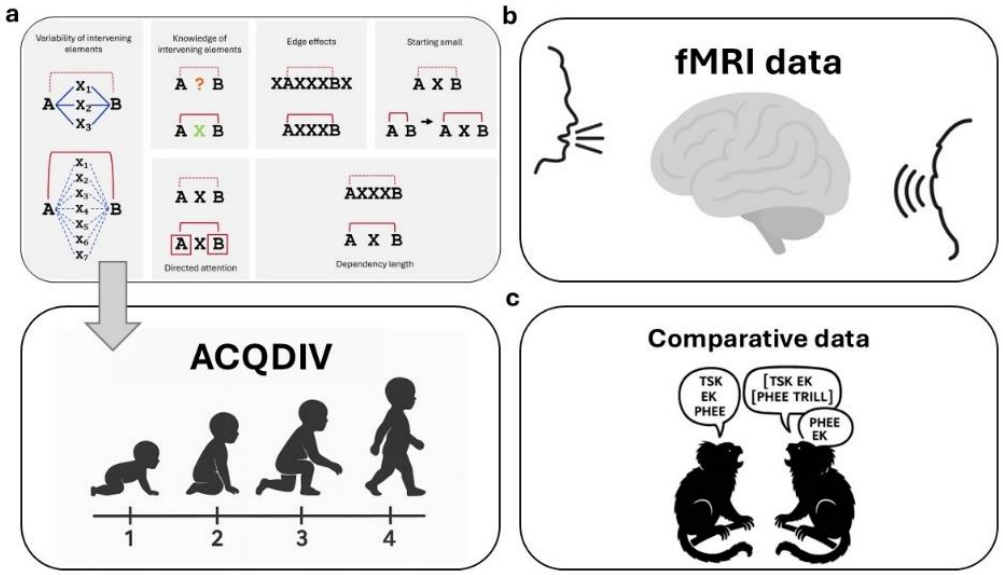


Figure 7. WP Locality aims to use a suite of approaches and methods to probe the evolution of adjacent and non-adjacent dependencies across linguistic and deep biological evolution. Our questions include, for example, **A)** what features in the input serve to scaffold dependency learning in children, **B)** how are dependencies of varying structural complexity processed in the brain and **C)** to what extent are primate vocal sequences characterised by similar dependency relationships.

WP Hierarchy

*PIs: **Bickel**, Garner, Giraud, Henderson, Meyer, Migliano; Collaborating PIs: Hervais-Adelman, Kazanina, Sennrich; Senior Researcher: Krapp, Olasagasti; Staff: Fehr, Gilford, Gruber, Hardegger, Kochert, Maksic, Morucci, Shaw, Shirakami, Su, Torres Orjuela; Associate Investigator: Mégevand, Preisig, Sauppe*

This work package is about the relation between the evolution of hierarchy in language and in action, a topic that has been difficult to tackle in the past because traditional models lacked neurobiological plausibility. For instance, they assumed unrealistically long-lasting access to previous context (over-long working memory and attention spans), either by overly constraining how hierarchies can interact with their linearization during incremental structure generation, or by encoding structure in a way that is difficult to map to real-valued brain activity and its multivariate probability distributions. Much effort of the WP therefore goes into developing alternatives. The workload is distributed over three tasks, Hierarchy Computation, Hierarchy Implementation and Hominin Planning.

The first approach, the **Hierarchy Computation Task**, takes predictive coding as its point of departure. We have implemented a baseline model for abstract latent representations of compositional constituents and probabilistic inference about them with Bayesian non-parametric models (i.e. models that allow parameters of flexible complexity and a flexible number of constituents). We are currently designing ways to model attention mechanisms (as in transformers) through strictly locally-activating networks (Hopfield networks), elucidating how these networks interact with the encoding of constituent structure based on the temporal binding of neural spikes. First results suggest successful identification of hierarchical composition in test data although it remains currently unclear whether the relevant operation are sufficiently distinct from sequencing. In parallel to this, we are exploring concrete encoding strategies based on this and other proposals (Mitropolsky, Collins & Papadimitriou 2021) and will next test them against neurophysiological measurements.

Another line of research starts from the observation that a hierarchy can be expressed as a directed rooted tree, a collection of nested sets or a partial ordering among elements. We describe various procedures to translate between these commonly used representations, shedding light on the information that each representation emphasises. To capture the interplay between the sequential form of a sentence and its underlying hierarchical structure, we introduce a new method of encoding hierarchies using surreal numbers (**Figure 8**) – a concept originating from mathematical order and set theory. This novel encoding, built on an extensive mathematical framework, offers several degrees of freedom for insertions and translations between surreal and real numbers. It also allows us to re-evaluate parsers of hierarchical structures of sentences used in the other tasks.

But even with new models of this kind, empirically differentiating hierarchy and sequencing continues to be a challenge, particularly in animal data. While we and other teams have made progress in inferencing potentially hierarchical and compositional structure in call sequences (Bosshard et al. 2024; Berthet, Surbeck & Townsend 2025; Leroux et al. 2023; Girard-Buttoz et al. 2022; Girard-Buttoz et al. 2025), we have not yet succeeded in probing specifically supra-regular (non-Markovian) structure in them, although even macaques can recognize supra-regular languages in artificial stimuli with relatively little training (Ferrigno et al. 2020). In response, we have refined and expanded grammar-induction methods (Jin et al. 2018) that successfully detect whether a sequence was generated by a regular or a supra-regular grammar, removing the requirement of very long sequences that has limited the utility of earlier approaches (Lin & Tegmark 2017; Sainburg et al. 2019). Initial results suggest that marmoset call sequences are right at the border between regular and supra-regular, potentially pointing to a mixed system. To explore this further we are now applying the method to a large array of data from animals and humans, both in communicative and noncommunicative behaviour.

Parallel to this is the **Hierarchy Implementation Task**, in which we have begun to survey candidate functions of specific neurophysiological activities, e.g., the function of specific Phase-amplitude couplings for computing nested relations, to generate hypotheses of how the brain processes the build-up of hierarchical structure over time. Here, we are particularly interested in interactions of such couplings between language-related brain areas to move towards a network-based understanding of processing. We use temporal response functions to probe coupling effects (Weissbart & Martin 2024) as a function of various measures of the developing linguistic structure (such as conditional probabilities of subtrees or subtree closures) in existing MEG recordings taken while subjects listened to stories (Gwilliams et al. 2024). To capture the emerging structure, we use a traditional incremental parser (Roark et al. 2009) but in the long term will profit from the modelling work in the Hierarchy Computation task for deriving biologically more sensitive measures of linguistic hierarchy.

Progress is interdependent with work conducted in the **Hominin Planning Task**. Here, we are concerned with the neural signatures of how non-linguistic hierarchies are processed. For this, we have piloted fNIRS recordings during stone tool production and are now in the process of solving several practical problems with this innovative methodology (e.g., sensitives to hair type) to optimize protocols that scale to both expert and naive producers and both WEIRD and non-WEIRD populations. One focus is on earlier technology (Oldowan from Australopithecus and Acheulean from Homo erectus), another on later, more complex technology (Levallois). In each case, the procedural units in tool production are identified (Perreault et al. 2013) and we are currently exploring a range of approaches to model how these units form hierarchies in order to track, one the one hand, the cumulative evolution of tool production and, on the other hand, to generate specific hypotheses on how to compare neural signatures in language and action.

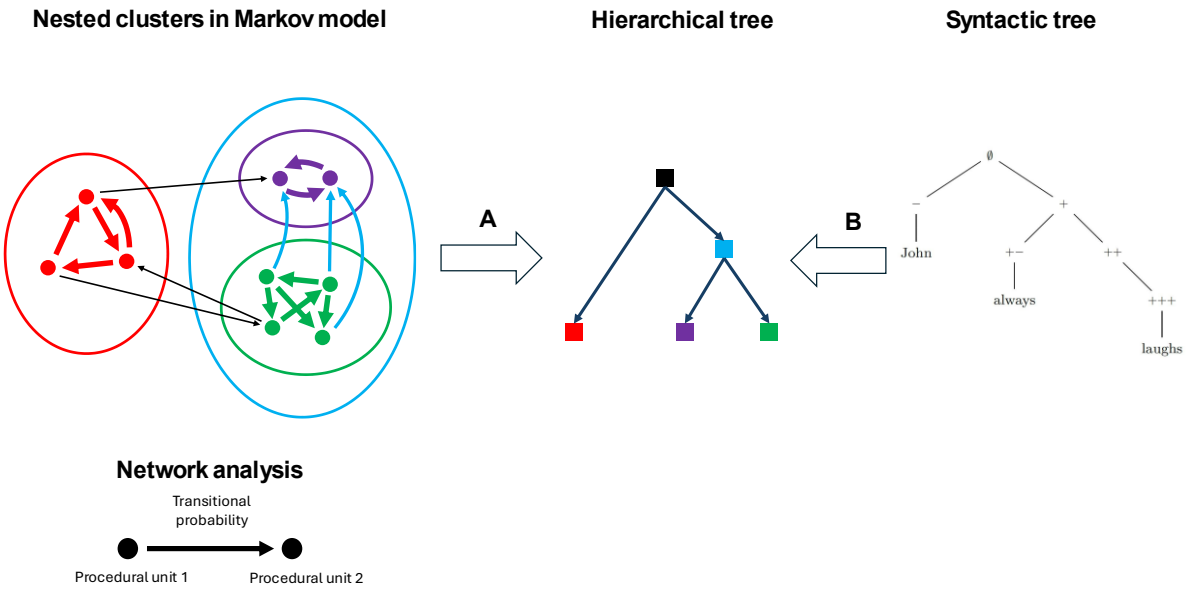


Figure 8. A) When comparing action and language, a common issue is that action sequences include cyclic subroutines, such as procedural units in tool production, that are mathematically incompatible with the acyclic nature of hierarchical trees. Adding transitions between nodes in Markov cycles, however, allows mapping a clustered network of subroutines to a hierarchical tree. **B)** The same tree can also be encoded via surreal numbers that can be mapped to real numbers (work in progress by Kochert and colleagues).

Table 5. Output for Syntax Project.

TASK	REFERENCE	OA	PID
HIERARCHY COMPUTATION	(Torres et al. 2024)	yes	-
CALL LOCALITY	(Engesser et al. 2024)	yes	OSF
CALL LOCALITY	(Leroux et al. 2025)	yes	OSF
CALL LOCALITY	(Cai et al. 2024)	yes	Supporting Information files, OSF and Zenodo
CALL LOCALITY	(Berthet, Surbeck & Townsend 2025)	yes	figshare

1.1.4 Project Meaning

Project Meaning explores how humans uniquely create and evolve linguistic meaning, investigating its cognitive, neural and evolutionary roots. First, **WP Meaning Behaviour** examines the evolutionary constraints and flexibility behind humans' ability to generate conventionalized meanings, comparing this capacity to communicative systems in animals. Second, **WP Meaning Computation** focuses on how lexical and compositional meanings are represented and processed in the brain, using behavioural, M/EEG and intracranial data. Finally, **WP WorldKnowledge** studies how complex knowledge and communication co-develop by comparing humans, non-human apes, and computational models to trace the distinctive evolutionary path of human language and cognition. As Project Meaning as a new project for Phase 2, the work has all freshly started and there is only minor legacy from Phase 1.

WP Meaning Behaviour

*PIs: Jäger, Manser, Migliano, Sennrich, Stoll, Van der Plas, **Widmer**, Zuberbühler; Collaborating PIs: Bangerter, Bickel, Borghesani, Burkart, Laganaro, Mansfield, Shimizu, Stadler, Townsend; Senior Researcher: Cathcart; Staff: Ahmad, Berthelin, Berthet, Cohen, Hellwig, Meunier, Protopapa, Rossini, Schamberg*

In contrast to most animals, humans relentlessly coin new words, replace old ones, and modify the meaning of words. How did this capacity for linguistic meaning evolve in humans? In language, processes of meaning change, and lexical innovation are not entirely arbitrary and may be at least partly shaped by the factors that are significant in animal communication systems. WP Meaning Behaviour aims at a better understanding of what exactly constrains humans to create conventionalised meaning, and to what extent are such constraints evolutionarily grounded in representational flexibility and conceptual (re-) mapping that is more widespread across animals. We investigate this at three different scales of evolution.

In the **Meaning Change Task**, we model the macroevolutionary process of meaning change when languages evolve over time and space. With historical data, we study the dynamics of gradual semantic change in language (Vedic Sanskrit) over extended time ranges. For this, we leverage language models that have been shown to perform well in determining gradual semantic change (Periti & Montanelli 2024) and use expert annotation of meaning change. We aim to develop an explanatory model of semantic change with time as a continuous variable that integrates language models' uncertainty and correlates results with historical data by studying the dynamics of gradual semantic change over extended time ranges. An initial set of experiments has shown that semantic predictions of a model trained without

linguistic preprocessing are only weakly correlated with expert annotations. To address this issue, we have developed a dedicated preprocessing pipeline that is able to lemmatize noisy Sanskrit text with sufficient accuracy.

The closely interlinked **Lexical Innovation Task** probes microevolutionary processes of emergence and spread of new terms in languages and focuses on identifying the social and linguistic drivers of lexical innovation. It aims to identify the social and linguistic drivers of lexical innovation, using interdisciplinary methods ranging from computational modelling and NLP to fieldwork in hunter-gatherer societies. It examines how social network structures, evolutionary mechanisms, and technological tools influence the creation and diffusion of new words across diverse cultural and technological settings, an aspect neglected so far (Altmann, Pierrehumbert & Motter 2011; Del Tredici & Fernández 2018; Stewart & Eisenstein 2018). At the present stage, we are extracting data from digital platforms such as Reddit and TikTok to identify novel terms using computational and NLP methodology.

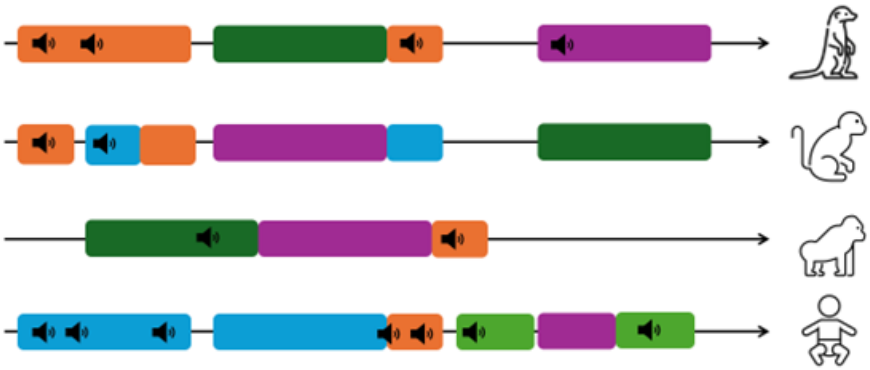


Figure 9. Data collection protocol across four target species over a comparable period of time of Animal Meaning Task.

With a cross-species approach, the **Animal Meaning Task** investigates the stability and development of meaning in vocalizations in four species: meerkats, chimpanzees, Sooty Mangabeys, and (infant) humans. We use experimental and observational data to specify the functional flexibility of vocalizations in their respective vocal repertoire to disentangle biological pressure from referential learning or inferential reasoning (Marler 1998; Oller et al. 2013; Thorpe 1961). The overarching idea of this task is to quantify the time each species spends in specific contexts (e.g., foraging, poly- and dyadic social interaction, grooming, etc.) and the number of vocalizations per context, which might provide insights into the context in which communication and form-meaning mapping emerge.

WP Meaning Computation

*PIs: Borghesani, **Kazanina**, Laganaro, Schwartz, Sennrich; Collaborating PI: Berthele, Brem, Giraud, Guggisberg, Meyer; Senior Researchers: Olasagasti; Staff: Couvreu, Desbordes, Feurstein, Franco, Licata, Piron, Saneei; Associate Investigator: Mégevand, Proix*

WP Meaning Computation studies how words meanings are organised in the brain and the neural mechanisms of creating a compositional meaning in real time. The Meaning Mapping and Silicon Meaning tasks focus on lexical organization, i.e. word retrieval challenges in bilinguals and clinical populations, and neural mappings of lexical semantics using language-model features and intracranial recordings

respectively. The Meaning Representation task extends the enquiry beyond individual word semantics, to neural mechanisms behind compositional meaning in language.

The **Meaning Mapping task** focuses on the structure of the lexico-semantic system, i.e. how meaning is represented and accessed. We specifically explore the interplay between concepts (meaning) and their linguistic labels (form), examining the nature of the relationship in bilinguals, and using situations where word retrieval is challenging. In multilinguals, we are working on a study on cognitive and neural (MEG data collection ongoing) dynamics of co-lexification (MacGregor et al. 2020), when two distinct meanings are represented as a single word in one language of a bilingual, and as two words in the other language. In parallel, we study word retrieval through the lens of Tip-of-the-Tongue states (Gollan & Silverberg 2001) using behavioural and EEG methods (data collection ongoing) with neurotypical young adults and older adults. This line of inquiry will also extend to clinical populations experiencing word-finding difficulties (particularly, patients with anomia).

In the **Silicon Meaning Task**, we are investigating how and where lexical-semantic meanings are represented in the brain by mapping LLM embeddings to neural activity. To this end, we have implemented a closed-loop paradigm (inspired by (Walker et al. 2019), using brain recordings and LLM-based embeddings (**Figure 10**). In collaboration with AI Mégevand at the hospital in Geneva we are using high temporal and spatial resolution data from intracranial recordings of patients with epilepsy undergoing surgery, during two days of listening tasks. This integrated approach seeks to unify neurocognitive theories with AI-based models of language. We are currently addressing two key challenges: (1) identifying the relationship between neural activity and word embeddings, and (2) dealing with the black-box nature of LLMs like GPT-2. To tackle the first, we are exploring regression-based methods. For the second, we are using interpretable embeddings—such as Lancaster Sensorimotor Embeddings (Lynott et al., 2020) —to make the model outputs more transparent and interpretable. To date, we have acquired data in 4 patients reading (1/4) or listening to (3/4) chapters of The Little Prince (first day, in green in Fig1) and then being presented with subject-specific optimized words (2/4) or short stories (2/4) (second day, in blue in **Figure 10**). We are currently expanding data acquisition to more patients.

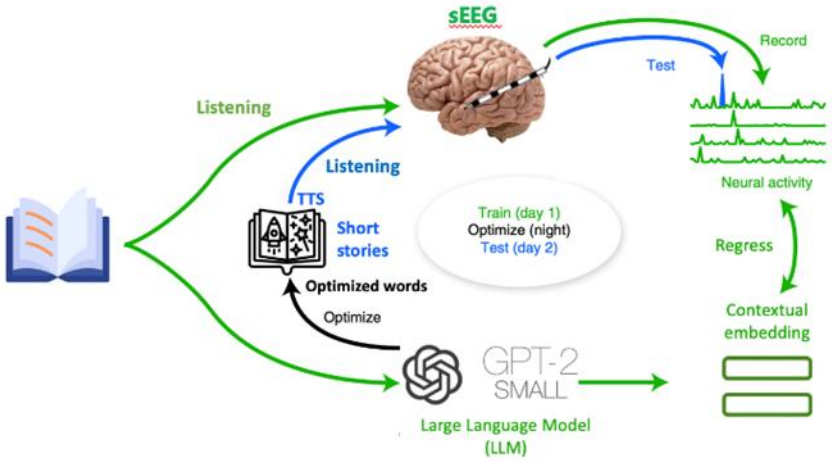


Figure 10. On the first day (green), the patient listens to *The Little Prince* while we record brain activities. During the night, we analyse the recorded neural responses using regression models to identify LLM embedding dimensions

most strongly associated with brain activity. Based on that, we gather lists of optimized word stimuli – designed to either enhance or suppress neural activation. In the end, we prepare a set of stories with these optimized words and on day 2 (blue), the patient is going to listen to the stories.

The **Meaning Representation Task** investigates the neural encoding of linear and hierarchical structure in wordlists and phrases respectively. For word lists, e.g. *coin second blue the biggest*, we expect a hippocampal theta-to-gamma Phase code that is evolutionarily old and based on the principles of linear sequence representation in non-human animals previously witnessed for locations (O'Keefe & Recce 1993; Buzsáki & and Watson 2012) and visual objects (Heusser et al. 2016; Lisman & Idiart 1995). We are currently testing this prediction in an MEG Experiment by comparing encoding for word vs. image sequences. We investigate whether sequences of verbal stimuli (i.e., word lists) are encoded using a theta–gamma Phase code similar to that observed for image sequences. We also examine how sequential reactivations (i.e., neural replay) of word and image sequences evolve with learning, providing insight into the format of linear mnemonic representations. In another MEG experiment we will compare word lists and sentences to directly test the impact of hierarchical syntactic structure on encoding dynamics.

WP WorldKnowledge

*PIs: Bavelier, **Borghesani**, Clément, Henderson, Sennrich, Townsend, Zuberbühler ; Collaborating PIs: Bickel, van der Plas; Staff: Bouffier, Dafreville, Semenov; Senior Advisor: Merlo*

This work package addresses the fundamental question of how complex knowledge representation and sophisticated communication co-develop, a question central to understanding the evolution of language and human cognition. We employ a comparative framework, contrasting humans, non-human great apes, and computational models to explore this relationship. This approach allows us to explore different points in the cognitive-linguistic landscape (**Figure 11**a) and shed light on the unique trajectory leading to human communication. Our central hypothesis posits that these groups vary along dimensions of knowledge and language sophistication. We aim to understand how human language, as it emerged through evolution, facilitates advanced knowledge representation, manipulation, and sharing – abilities seemingly unique among animals and not yet fully matched by computational models. This investigation is structured into four complementary tasks (**Figure 11**b-e) that utilize comparative methodologies across biological and artificial systems to dissect the intricate relationship between cognition and language. By addressing key questions about cognitive representation, rule learning, instruction following, and multilingual knowledge organization, this research aims to provide crucial insights into the foundations of human cognitive uniqueness, and the principles underlying intelligence in both biological and artificial forms.

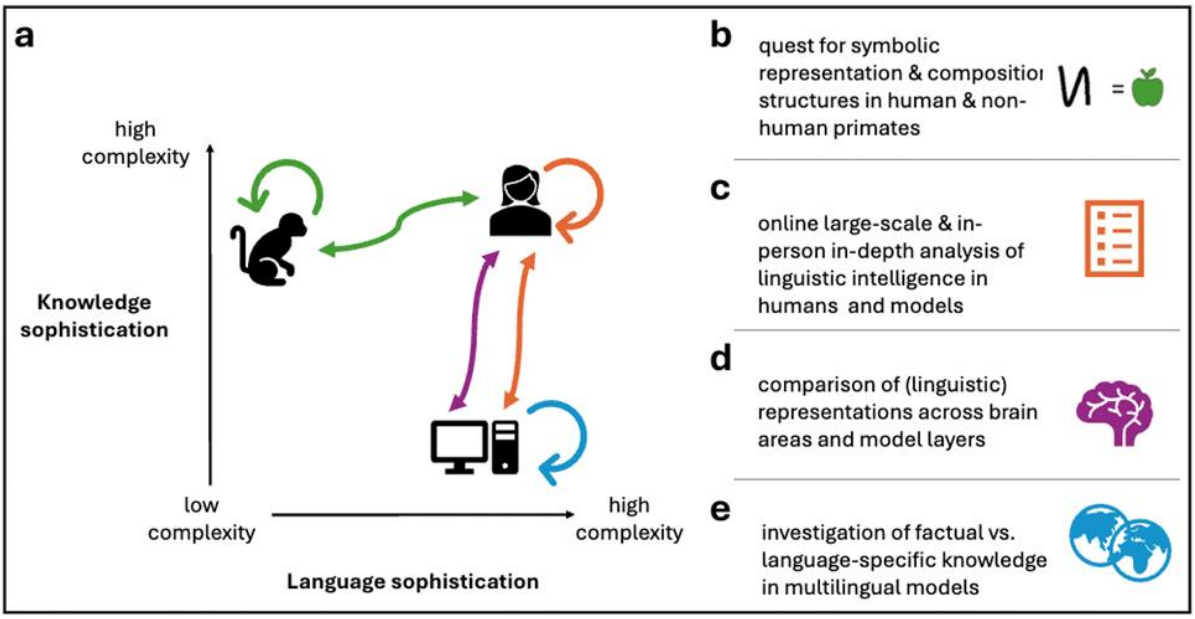


Figure 11. A) Schematic representation of how the WP tasks plan to tackle the basic problem of how cognitive complexity relates to communicative complexity, **B)** how humans directly compare to non-human apes in terms of their representational abilities, **C)** how individual differences in human linguistic relate to other cognitive performance, **D)** how linguistic performance is linked to brain function and **E)** how knowledge is represented in silico.

The **Comparative Cognition Task** (**Figure 11**b) assesses knowledge representation complexity in non-human great apes versus humans. We are comparing the impact of symbolic representations on event cognition via touchscreen/eye-tracking experiments (ape data collected Jan 2025; human data collection Apr/May 2025). Then, we will probe apes' understanding and production of compositional communication structures (protocols in development, stimuli prep Apr 2025, data collection Jun 2025).

Rules Task (**Figure 11**c) probes linguistic intelligence – the capacity for pattern extraction and rule generalization from sparse input (for example, 8 sentences following a pattern of subject-verb agreement in singular or plural, or the interplay between agent and patient in active and passive sentences). Phase one will establish human performance benchmarks on three Blackbird Language Modelling (BLM; (Merlo 2023)) problem types (agreement, causative, object drop) through large-scale online testing (French: Summer 2025; English: Fall 2025). Phase two will use in-depth, in-person testing (French, Fall 2025) to link BLM performance ('object drop', 'causative') with working memory and analogical reasoning, identifying relevant neuropsychological factors.

Instructions Task (**Figure 11**d) examines the human ability to follow novel verbal instructions, a key adaptive advantage of language. We have now completed fMRI data collection and have begun to track neural representational changes from processing written syntactically varied commands (e.g., relative/passive clauses) to motor execution in relevant brain regions, ranging from occipital visual regions to temporo-frontal regions known to be involved in semantic processing and frontal motor regions. Comparing these neural representations with those of computational models, we aim to map the different computational stages to specific brain regions.

Silicon Knowledge Task (**Figure 11**e) investigates knowledge organization (factual vs. linguistic) in multilingual Large Language Models (LLMs). We test if grammatical accuracy in prompts (e.g., correct gender marking: Russian *Sofia umerla/*umer* (Sofya.Fem.Nom died.Fem/died.Fem) impacts factual knowledge retrieval using the Multilingual Language Model Analysis (MLAMA) benchmark. As initial results were inconclusive, we are expanding language coverage and developing improved MLAMA templates suitable for diverse linguistic typologies (e.g., V-final languages) and model architectures (e.g., autoregressive), placing target information strategically for fairer comparisons.

Table 6. Output for Syntax Project.

TASK	REFERENCE	OA	PID
CALLLOCALITY	(Lahiff et al. 2025)	yes	figshare

1.1.5 Project Interaction

Project Interaction examines the role of interdependence (the dependence of an individual's fitness on another individual's fitness) as an evolutionary driver of complex communication. **WP Information Integration** explores how the brain integrates multimodal signals featuring both referential content and speaker-related information, including non-linguistic, behavioural modalities. Integration is also explored in offline processes like consolidation during sleep and interindividual processes in conversation, using hyper-scanning. **WP Information Throughput** investigates neural structures, communication capacities, and psychological mechanisms that support interdependence across species and across typically and atypically developing children and adults.

WP Information Integration

*PIs: Dellwo, Grandjean, **Hervais-Adelman**, Laganaro, Magimai-Doss, Manser, Meyer, Schwartz; Collaborating PIs: Daum, Giroud, Hahnloser, Townsend, Zuberbühler, Borghesani; Staff: Filippa, Iliopoilos, Lavezzo, Mauchand, Piette, Sabov, Slaats, Varano*

Speech and other mammalian vocal signals encode referential content, but also information about speaker identity, arousal or attitude to construct shared meaning (Figure 1A). Vocalizations are further co-produced with visual signals, like posture, facial expressions, articulatory movements or gestures, which all impact comprehension, impression formation and intrapersonal and interpersonal synchrony. This work package uses time-resolved brain imaging protocols to explore the neural integration of multimodal signals in constrained and naturalistic interactions. Tasks focus on the role of prosody and speaker identity in comprehension (**Neural Integration Task**), acoustics of infant vocalizations and their effects on emotional appraisal and cuteness (**Behavioural Integration task**), and integration of speech, cardiac and oscillatory functions (**Hyperscanning Task**). Another goal (**Clinical Intervention Task**) is to probe the role of sleep in consolidating language learning.

The **Neural Integration Task** aims to understand the temporal dynamics, including those of neural processes, underlying the integration of paralinguistic features and linguistic content in conversation. Since determining speaker identity quickly is crucial for interpreting utterances in multi-talker environments, we asked whether speakers are more distinctive at the start of an utterance (Figure 1B). We collected and analysed speech corpora from natural conversations and constrained sentence-reading tasks, employing both traditional features used for speaker identification (MFCCs) and modern vector representations of identity derived from neural-network embeddings (x-vectors; Figure 1C). The Euclidean distance between the vectors representing the acoustics or identity embedding of speakers was used as a proxy for the distinctiveness of speakers' voices. Supporting our hypothesis, preliminary

results show that the distance between speakers decreases over the first seconds of an utterance for both x-vectors (Figure 1D) and MFCCs. Ongoing work will compare natural speech and structured reading tasks, and future work will investigate how listeners integrate linguistic and identity cues to create meaning, employing M/EEG brain imaging.

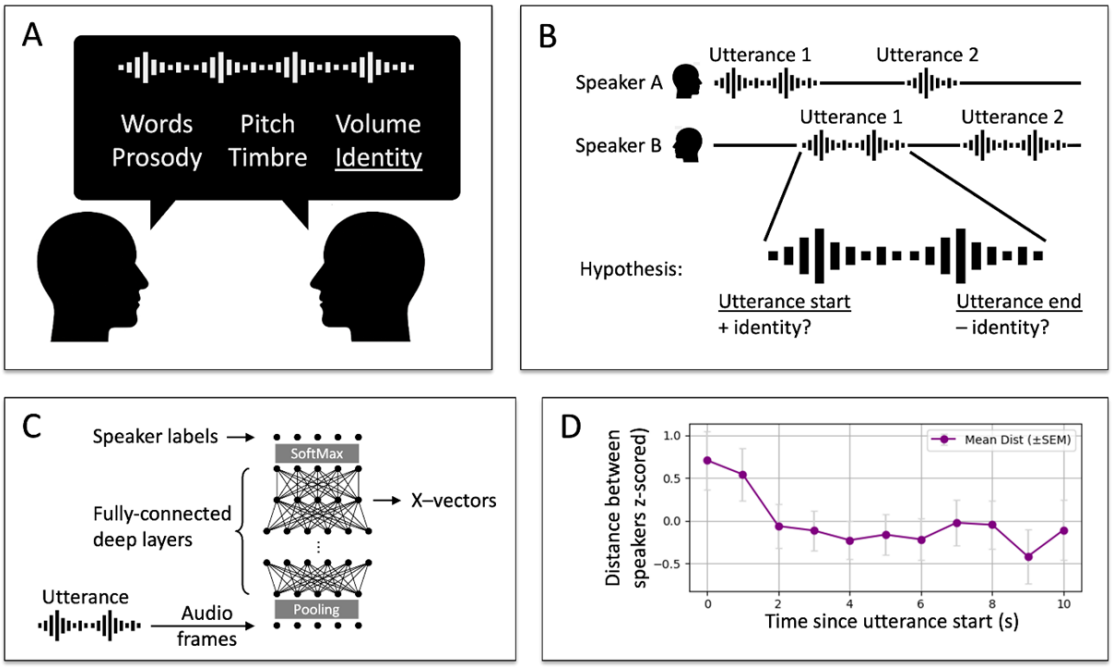


Figure 12. Temporal dynamics of speaker identity in conversation. **B)** Analysis of acoustic features **C)** of speech corpora using x-vectors **D)** reveals that speaker distinctiveness decreases within the first seconds of an utterance.

While extensive research has explored speech at linguistic and phonetic levels, the underlying neurophysiological mechanisms, particularly in natural conversation, remain largely unknown. How are multisensory modalities deployed and neurally integrated in real time during conversations? To address this, the **Hyperscanning Task** is developing an EEG hyperscanning platform to measure multiple participants simultaneously and evaluate synchrony at both individual (e.g., cardiac-neural-speech alignment) and interindividual (e.g. neural synchrony between interlocutors) levels. As an initial step toward integrating four parallel recordings, we are currently setting up an experiment to investigate the relationship between speech, cardiac and oscillatory function. Our set-up includes EEG, ECG, and eye-tracking data from 20 dyads during: (1) a joint counting task, promoting rhythmic turn-taking, and (2) natural conversation. Pilot measurements are under way, data collection will conclude by June 2025. Depending on outcomes we develop protocols for cross-cultural work together with TTF Instrumentation.

As we go through life, the way we learn and store new words changes. While young adults typically integrate novel words with relative ease, older adults often experience greater difficulty. Concurrently, quality of deep sleep gradually changes with age (Helfrich et al. 2018). Since sleep plays a key role in strengthening new memories, these changes could directly affect how well new words are learned and remembered. The Clinical Intervention Task investigates whether reducing the quality and propagation of slow waves during deep sleep (as observed in ageing) via targeted auditory stimulation under EEG monitoring (Fehér et al. 2023) impairs the transfer of memory traces from the hippocampus to

neocortical language networks, thereby hindering lexical integration for newly learned words. Functional MRI data will be collected while participants perform memory encoding and recall tests. Data collection is planned to start in summer 2025. We already pretested both the experimental paradigm (Bars et al. in prep.) and stimulus set (Franco, Glize & Laganaro 2025) and they are well-suited to the aims of our study, in which participants will learn 2 matched lists of new (rare) words and will be assessed after a standard night and after a night of disrupted sleep in a within-participant cross over design.

Before they learn to talk, humans (and other primates) communicate via vocalizations which integrate a variety of identity-related, social, and emotional information. The **Behavioural Integration Task** has constructed a database of 360 infant vocalizations to examine how this information is encoded into acoustic signals and appraised by adults to produce appropriate judgements and behaviour. An acoustic-perceptual study revealed clear acoustic markers of infant age and emotional valence which were successfully decoded by adults to form impressions of emotions and cuteness, especially as infants aged after 6 months. We are launching a second study using fMRI to examine how these signals integrate in the brain, focusing on how cuteness elicits caregiving behaviour. We analysed the infant vocalizations using two types of feature representations: (a) short-term spectrum-based feature representation and (b) feature representations learned by neural networks trained on infant vocalizations. We achieved above-chance performance for valence estimation (F1 = 0.589). Work on extending these methods to vocalizations of other primates is in progress. In parallel, we are constructing databases of primate (baboons & vervets) and meerkat vocalizations (currently, >600 vervet vocalizations, >300 baboon vocalizations, and >400 meerkat vocalizations).

WP Information Throughput

*PIs: Bangerter, Bickel, Bshary, **Burkart**, Cerrito, Furrer, Grandjean, Hahnloser, Mazzarella, Schaer, Zuberbühler; Collaborating PIs: Bavelier, Clément, Dellwo, Mansfield, Manser, Sennrich, Stadler, Stoll, Townsend; Senior reseachers: Cathcart, Vaughan; Staff: Belli, Ayers, Belli, Chakravorty, Ciuffi, Ilaridou, Latrèche, Phaniraj, Rüst, Ulrich; Senior Advisor: van Schaik*

Phase 1 research established the role of interdependence and cooperation as drivers of advanced communication using e.g. cooperative breeding marmosets. This work package continues by (1) deepening investigation into potential behavioural mechanisms and neuroanatomical substrates and (2) broadening investigation in the wider phylogenetic tree. We examine a suite of behavioural mechanisms in the service of cooperation, including mutual gaze, social referencing, partner choice or establishing shared goals, as well as neuroanatomical substrates like the amygdala. We also adopt a phylogenetic approach to understand the evolutionary conditions that may have facilitated information throughput, as measured in a common metric bridging text, speech and animal vocalisations.

The **Social Competence Task** aims to identify conserved neural and behavioural markers that contribute to the emergence of joint attention and language by investigating the interplay between mutual gaze (via eye-tracking), vocal behaviour, and amygdala anatomy across species and during ontogeny in marmosets as well as autistic and neurotypical children. his interplay is central to early social communication and may reveal developmental mechanisms underlying atypical social behaviours in autism (Charman 2003). We have developed a setup with an acoustic camera and started data collection of the ontogeny of verbal and non-verbal communication in marmosets. For young autistic children, we are expanding the data set of cerebral MRI data and have leveraged a subset of our longitudinal sample (n=77 participants, 337 assessments) for whom we used the Early Social Communication Scale (Mundy et al. 2003) to understand the relationship between joint attention and language development (Figure 1). When we grouped children by their expressive language development, we found that initiation of joint

attention (IJA) was consistently higher across all ages in those who developed language more rapidly. In contrast, response to joint attention followed an age-related pattern that mirrored the trajectories of expressive language in each group, which implies that changes in RJA may reflect or support ongoing language development.

The **Information Load Task** quantifies information content in acoustic signals to establish robust methodologies for cross-species and cross-linguistic comparative analysis of vocalisations. Our cross-linguistic comparison approach involves contrastive entropy assessments between phonemic and orthographic transcriptions, complemented by mathematical derivations of conditioned entropy relationships across hierarchical linguistic structures, and elucidates emergent properties from constituent units (Klafka & Yurovsky 2021). To estimate estimates at the level of the language faculty instead of individual languages, we have begun to formulate phylogenetic models across a forest of phylogenies with different typologies and ontogenetic models over longitudinal data in ACQDIV. We are concurrently implementing Shannon's information-theoretic framework also for animal communication analysis, having derived an inequality connecting time series predictability to conditional differential entropy (Fang et al. 2019; Shannon 1951). By developing autoregressive deep learning models to predict spectral characteristics of animal vocalizations (including humans), we are establishing indirect quantitative metrics of information load across species' communicative systems. We expect to see that higher vocal learners will have more complex signals and therefore be less predictable.

The **Hypercooperation Task** investigates the exceptional levels of large-scale non-kin cooperation demonstrated by humans. This is often attributed to their ability to spontaneously establish cooperative intent, which we hypothesise is greatly enhanced with language (in both adults and children (McClung et al. 2017; McClung et al. 2024). To test this, we are preparing a series of experiments in which human participants play interactive games in ecologically valid environments. Our first experiment simulates the mutualistic relationship between cleaner wrasse and their client fish observed in reefs. By taking a game-theoretical approach, we explore how pairs of humans, playing as cleaner and client fish, converge on cooperative strategies while manipulating their ability to communicate and their knowledge of payoff structures. The results from the first experiment will inform the design of a more complex version of the game with multiple players playing simultaneously, possibly online. Our study aims to shed light on how language regulates the establishment of shared goals, reputation building through gossip, and conditional reciprocity in large-scale human cooperation.

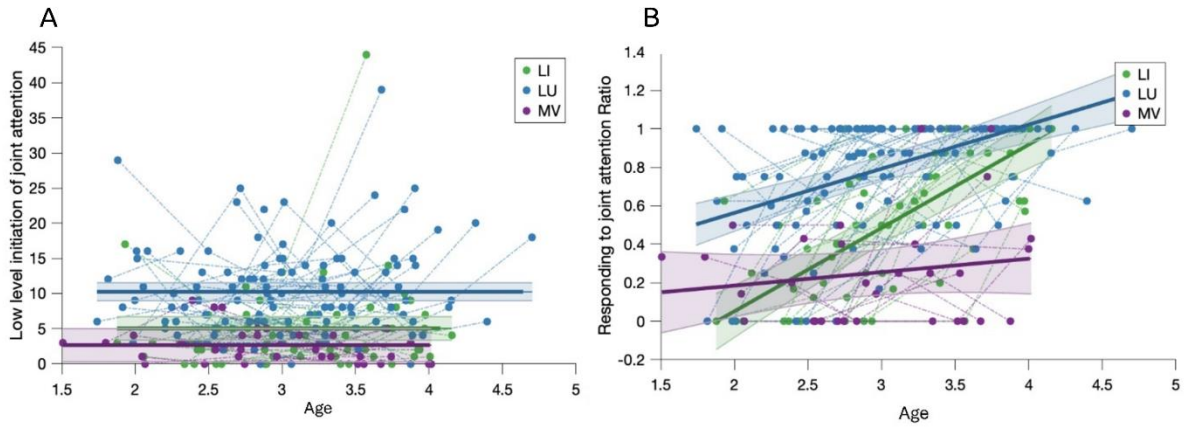


Figure 13. A) Level of joint attention initiation and **B)** responding to joint attention, in children with autism with different language profiles. Language Impaired (LI, characterized by important changes in language structure,

represented in green), Language Unimpaired (LU, with minimal language difficulties, represented in blue) and Minimally Verbal (MV, with limited verbal skills, represented in purple).

Table 7. Output for Interaction Project.

TASK	REFERENCE	OA	PID
HYPER COOPERATION	(McClung et al. 2024)	Yes	figshare
NEURAL INTEGRATION	(Friedrichs et al. 2024)	Yes	-
SOCIAL COMPETENCE	(Burkart et al. 2025)	preprint	No data associated
SOCIAL COMPETENCE	(Burkart & Southgate 2025)	preprint	No data associated
SOCIAL COMPETENCE	(Sehner et al. 2025)	Yes	OSF
SOCIAL COMPETENCE	(Cerrito et al. 2024)	Yes	Data gathered from other studies

1.1.6 Transversal Task Forces

TTF Ethics has delivered a combination of educational and research activities in Year 5.

Educational: two introductory courses during the Winter School 2025; six Brown Bag lunches in Year 5; one-day workshop on "Integrity in Research" and "Ethical Aspects of Research with Human and Animal Participants" conducted in June 2025 at each home Institution; on-demand consultation service for NCCR researchers.
Research: two articles in conference proceedings: on the harmful use of technologies and on the risks of long-term use of transcranial direct-current stimulation (tDCS) and their ethical implications ((Malbois, Borghesani, et al. 2025; Malbois, Hurst-Majno, et al. 2025)).

PI: Hurst

TTF Concepts has maintained the mandate of enabling bottom-up initiatives for translating and transmitting empirical breakthroughs into the wider theoretical perspective, in Phase 2 now headed by a larger team of PIs. While we have produced several big-picture and review papers along these lines (see **Table 8**), TTF Concepts has not yet been formally activated. The envisaged modus operandi is by recruiting ECRs on an ad-hoc basis to provide conceptual clarification of relevant empirical progress and to ensure its dissemination to a wider interdisciplinary readership.

PIs: Bavelier, Bickel, Kazanina, Weber, Zuberbühler; Senior Advisors: Glock, Van Schaik

TTF Datascience continues to support the NCCR for data-related issues with help of the NCCR@LiRI staff. In the past two years, a total of 224 tickets has been registered, from data processing and language model training to Bayesian statistics and computing infrastructure. The TTF includes 3 WPs: **WP Databases** maintains the data management pipeline built in Phase 1 to keep track of NCCR publications and open datasets, and the ACQDIV corpora on language acquisition; **WP MachineLearning** develops the VoCallBase database of animal communication, including CallMark, a web application for annotating vocalizations; **WP Statistics** provides statistical expertise across all WPs. TTF DataScience received several internal grants covering diverse topics, e.g. gaze detection in humans and apes, development of large naturalistic intracranial EEG, a dataset of natural conversation recordings.

PIs: Furrer, Hahnloser, Stoll

TTF Instrumentation developed the MicroVibro tool, a smart sensor for baboon vocalization recording and analysis during mother-offspring interactions in the first months of life. The device contains multiple recording channels to tell apart vocalisations originating from the mother and those originating from the infant. Sound quality is currently evaluated, and the design is further adjusted for sound optimization, durability and comfort. Further, the TTF has surveyed and downloaded existing interaction game resources, e.g., Pear stories, MPI space games and SCOPIC (Social cognition Parallax Interview Corpus). Most data are available from Pear stories (693 speakers, ~80 distinct languages). The larger goal is to set up a lab to test dual EEG/fNIRS recordings of participants doing interaction games in field settings, in collaboration with the Hyperscanning task (WP Information Integration).

PIs: Bangerter, Hahnloser, Jäger, Meyer, Migliano, Stoll, Townsend; Associate Investigator: Dimov

TTF DigitalDataGeneration aims to provide a user-friendly, searchable database of online language and cognitive tasks for the NCCR researchers. Following a user survey, the TTF has identified key priorities, converged on Python and GitLab use, and designed a task library structure searchable by various criteria (see demo). Externally, we have participated in the EPFL Hackathon 2025 - AI model adaptation of ASR for children's speech, as well as engaged with AI-for-education.org also with a focus on ASR.

PIs: Bavelier, Borghesani, Brem, Golestani, Jäger, Laganaro, Zuberbühler

Table 8. Output for Transversal Task Forces.

TTFS	REFERENCE	OA	PID
ETHICS	(Malbois 2025)	yes	No data associated
CONCEPTS	(Bickel, Giraud, Zuberbühler & van Schaik 2024)	yes	No data associated
CONCEPTS	(Bausman & Weber 2024)	yes	No data associated
CONCEPTS	(Reilly et al. 2025)	yes	No data associated
CONCEPTS	(Weber 2025)	Yes	No data associated
CONCEPTS	(Cathcart & Bickel 2024)	yes	No data associated
CONCEPTS	(Berthet et al. 2025)	Yes	No data associated
CONCEPT	(Stoll et al. 2025)	preprint	Included in the manuscript
CONCEPTS	(Cerrito et al. 2025)	preprint	All data are available in the main text
CONCEPTS	(Glock 2024)	No (book)	No data associated
CONCEPTS	(Glock 2025)	yes	No data associated
CONCEPTS	(Büttner & Glock 2024)	yes	No data associated
CONCEPTS	(Fröhlich & van Schaik 2025)	yes	No data associated

1.2 New Developments in research structure

New developments in the NCCR's research infrastructure have been achieved by means of two primary instruments, i.e. Special Interest Groups (SIGs) and Innovation grants.

1.2.1 Special Interest Groups (SIGs)

SIG Canid Cognition

The communication-cooperation hypothesis suggests that species with high cooperative demands evolve complex communication. While most primates cooperate to some degrees, humans are unique in terms of cooperative childcare, foraging, territory defence and cultural behaviour. Henc, this SIG has given itself the task of investigating communication in a group of animals that are more human-like in terms of cooperation than any non-human primate species, the canids. Wolves and dogs are of particular interest, with dogs having lost some of their original cooperative capacities during 10k years of domestication. The SIG Canid Cognition has received a 1.6M international WEAVE grant – co-funded by the SNSF and Austrian Science Foundation - to investigate the development, mechanisms and function of visual and auditory communication in wolves and free-ranging dogs.

PIs: Bickel, Cerrito, Giraud, Meyer, Townsend, Zuberbühler; Staff: Wirobski

SIG Computational Models of Evolving Language

The SIG Computational Models of Evolving Language fosters interdisciplinary research on computational models and their role in understanding language evolution. With a diverse membership across fields and institutions, the group has met monthly over the past year to share advances, discuss challenges, and critique research. Key collaborative activities include harmonising methods for comparing artificial and biological data, exploring Language Models as research subjects and investigating their societal implications. A significant collaborative output is the development of Open Science recommendations, promoting transparency and reproducibility, which will be soon shared with the NCCR Community.

PIs: Borghesani, Garner, Hahnloser, Henderson, Sennrich, Van der Plas; Senior researcher: Olasagasti; Staff: Bouffier, Samo, Saneei, Su; Senior Advisor: Merlo; Associate Investigator: Proix;

SIG Neuroscience of Language

The SIG Neuroscience of Language fosters idea exchange and collaboration among NCCR members from diverse sub-areas, including clinical, cognitive, and computational neuroscience with monthly hybrid meetings. It serves as a mechanism to provide feedback of ongoing work, especially important for ECRs co-supervised by PIs from different home institutions. It interacts with key NCCR resources, such as the NEBULA101 open dataset for the study of language aptitude (Rampinini et al. 2025) and the curated intracranial dataset by Megevand, Proix and Nabe. Finally, it seeks its international reach with invited speakers and methods workshops.

PIs: Bavelier, Borghesani, Giraud, Giroud, Golestani, Guggisberg, Hervais-Adelman, Kazanina, Laganaro, Schaer, Schwartz; Senior researcher: Olasagasti; Associate Investigators: Preisig, Proix, Sauppe

SIG Cetacean Communication

SIG Cetacean Communication is currently working on the vocal behaviour of orcas, with a project on biphonation, one of the most intriguing aspects of Orca communication. Biphonation allows individuals to produce two distinct calls simultaneously, possibly generated by two different sound sources within their nasal structures. Like humans, and unlike non-human primates, Orca sound

production requires considerable neural control, which likely paves the way to large signal repertoires that can be coopted for a range of functions, including individual recognition, group identity markers, coordination of cooperative behaviour and other complex social functions. The current goal of the SIG is to automate Orca call analysis with WHISPERseg, an NCCR-generated call detection algorithm in collaboration with TTF DataScience.

PIs: Hahnloser, Townsend, Zuberbühler

Table 9. Output for Special Interst Groups.

SIG	REFERENCE	OA	PID
NEUROSCIENCE OF LANGUAGE	(Hervais-Adelman & Townsend 2025)	Yes	No data associated
CETACEAN COMMUNICATION	(Rychen et al. 2023)	Yes	Zenodo

1.2.2 Innovation Grants

"The neural dynamics of novel form-meaning associations" uses MEG to investigate the cognitive and neural substrate underlying the creation of novel form-meaning associations. The number of shared semantic features determines whether people perform an over-extension (i.e., adapt an existing lexical item to cover the novel concept) or a lexical innovation (i.e., create a novel lexical item ad hoc for the novel concept) (Brochhagen et al. 2023). A word learning task with a set of novel stimuli varying along four semantic dimensions (colour, movement, sound, emotion) was piloted, with the results currently being analysed; the MEG Phase of the project will start in the fall of 2025.

PIs: Bickel, Borghesani, Laganaro, Mansfield

"Flexible compositionality in a language trained bonobo" tests the hypothesis that human syntax is unique in its compositionally generative way - words can be recombined to produce an infinite number of meanings. We tested the claim with Kanzi, a language-trained bonobo housed at ACCI (Iowa, USA). Kanzi possesses a repertoire of about 200 abstract symbols that refer to real-world objects or actions. In the experiment, he was asked to refer to objects for which he did not possess a specific symbol. For example, he was given the opportunity to request three types of cheese, although he only possessed one general symbol for 'cheese'. Was he able to borrow from his existing repertoire to further specify what kind of cheese he preferred from a selection? Experiments were conducted in early 2025, shortly before Kanzi's death, and videos are currently being coded and analysed.

PIs: Bickel, Townsend, Zuberbühler

"Semantic Remapping" investigates cross-domain semantic mappings in human brains and artificial neural networks using lexical conflations such as SKIN and BARK (that are often represented by the same word, e.g., crossing domain from animals to plants. The project will test whether LLMs also treat such conflations as less surprising than gross sense violations, which would require a rich model of spatial similarities and cross-domain mapping.

PIs: Mansfield, Sennrich; Staff: Licata, Van Ommen; Associate Investigator: Proix

"Using immersive virtual reality (iVR) in conversational contexts for the assessment of language in people with aphasia and cognitive decline in aging" employs iVR for evaluation and diagnostics in a close-to-real-day life context, assessing whether iVR has an advantage over standard assessment in

people with mild aphasia, and explores the iVR's potential for predicting neurocognitive disorders in aging.

PIs: Giroud, Laganaro

"A pilot study towards the development of a speech-neurofeedback to boost aphasia rehabilitation" explores the possibility of a rehabilitative intervention based on a Brain-Computer Interface for patients with aphasia, especially for severe cases. The grant lays the foundation for such a project via a pilot study in healthy participants, with an amended ethical protocol is currently under review and data collection planned immediately after.

PIs: Guggisberg; Staff: Marchesotti

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Appendix : Output from Phase 1

Supplementary Table 7. Output from Phase 1 Work Packages.

WP	REFERENCES	OA	PID
NeuroComp	(Mach et al. 2024)	yes	connectomeDB
NeuroComp	(Van De Ville & Liégeois 2024)	yes	No data associated
SignalRec	(Fehr & Henderson 2024)	yes	huggingface
JointAction	(Tilston, Holler & Bangerter 2025)	yes	-
JointAction	(Heesen et al. 2025)	yes	figshare
JointAction	(Godard, Burkart & Brügger 2024)	preprint	OSF
JointAction	(Adriaense et al. 2024)	preprint	-
JointAction	(Morozova et al. 2024)	yes	Data gathered from other studies
JointAction	(Bangerter et al. 2024)	yes	Upon request
MentalState	(Alexander 2025)	yes	No data associated
MentalState	(Taylor et al. 2024)	yes	PeerJ
MentalState	(Gönül & Clément 2024)	yes	OSF
CompuLang	(Zaghir, Bjelogrlic, Goldman, Ehrsam, et al. 2024)	yes	Github
CompuLang	(Zaghir, Naguib, et al. 2024)	yes	No data associated
CompuLang	(Zaghir, Bjelogrlic, Goldman, Bensahla, et al. 2024)	yes	Data gathered from other studies
CompuLang	(Zaghir, Bjelogrlic, Goldman, Aananou, et al. 2024)	yes	github
CompuLang	(Shaitarova et al. 2024)	yes	zenodo
CompuLang	(Rooein et al. 2024)	preprint	-
Arbitrariness	(Watson et al. 2024)	yes	OSF
Phylo	(Herce & Bickel 2025)	yes	gitlab
Phylo	(Takahashi, Glaser & Ranacher 2024)	yes	zenodo
Phylo	(Cathcart & Jäger 2024)	yes	zenodo
Phylo	(Cathcart 2024)	yes	zenodo
EmotionIntegration	(Driscoll et al. 2025)	yes	Mendeley
EmotionIntegration	(Gruber et al. 2025)	yes	No data associated
SemanticRoles	(Isasi-Isasmendi et al. 2025)	yes	OSF
SemanticRoles	(Egurtzegi et al. 2025)	yes	OSF
SemanticRoles	(Wilson et al. 2024)	yes	OSF
SemanticRoles	(Nellissen et al. 2024)	yes	figshare

SemanticRole	(Brocard, Vanessa A. D. Wilson, et al. 2024)	yes	OSF
SemanticRoles	(Brocard et al. 2025)	yes	SWISSbase
SemanticRoles	(Huber et al. 2024)	yes	-
SemanticRoles	(Isasi-Isasmendi et al. 2024)	yes	OSF
Compositionality	(Torres et al. 2024)	yes	-
SpeechArticulation	(Lancheros & Laganaro 2024)	yes	yareta
StucturePlanning	(Torres et al. 2024)	yes	
StucturePlanning	(Piette et al. 2024)	preprint	github
ProsodyToMeaning	(Oderbolz, Poeppel & Meyer 2025)	yes	-
ProsodyToMeaning	(Oderbolz et al. 2024)	yes	OSF
ProsodyToMeaning	(Degano et al. 2024)	yes	figshare
TemporalHierarchies	(Piette et al. 2024)	yes	github
TemporalHierarchies	(Déaux et al. 2024)	yes	Supporting information
EarlySurround	(Wegdell 2025)	yes	-
EarlySurround	(Wegdell et al. 2025)	preprint	-
SocialContext	(Mine et al. 2024)	yes	Supplementary materials
Aptitude	(Rampinini et al. 2025)	yes	openneuro
Aptitude	(Rampinini et al. 2024)	yes	will be made available via separate publication
DigiDis	(Haugg et al. 2025)	yes	upon request.
DigiDis	(Frei et al. 2025)	yes	OSF
DigiDis	(Franco, Glize & Laganaro 2025)	yes	yareta
DigiDis	(Fraga-González et al. 2025)	yes	OSF
DigiDis	(Franco & Laganaro 2024)	yes	yareta
DigiDis	(Bhadra, Giraud & Marchesotti 2025)	yes	OSF
NeuroMod	(Farcy et al. 2024)	yes	Upon request

Supplementary Table 8. Output for Phase 1 TTFs.

WPs	Title	OA	PID
Databases	(Graff et al. 2025)	yes	zenodo
MachineLearning	(Gao et al. 2024)	yes	github
MachineLearning	(Gu & Hahnloser 2024)	yes	github
MachineLearning	(Gao 2024)	yes	Data taken from other studies
ASR	(Ben Mahmoud et al. 2024)	preprint	github

ASR	(Sarkar & Magimai.-Doss 2025)	yes	-
ASR	(Sarkar & Doss 2024)	preprint	-
ASR	(Sarkar et al. 2025)	yes	Data taken from other study