Predictive Processing and Cognitive Development

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The ability to acquire new cognitive capacities is the hallmark of the human mind. Emerging predictive processing (PP) accounts promise to offer a unified, mechanistic perspective on the neuro-functional realization of this complex process. The acquisition of any given cognitive capacity can be depicted as a specific stage of the continuous prediction error minimization process. This stage is characterized by distinct functional profiles, unique patterns of neuronal activation in crucial brain areas, and the refinement and flexible adaptation of motor programs to new processing challenges. In this paper, I will suggest that PP is a good conceptual partner for accounts of enculturation.

Enculturation is the idea that socio-culturally shaped cognitive processes emerge from an individual's scaffolded, embodied interaction with its cognitive niche. This structured engagement with specific, socio-culturally developed patterns in the niche transforms the overall cognitive capacities of an individual (Menary 2013; Menary 2015a). The process of enculturation is associated with significant changes in the functional and structural properties of the brain. Furthermore, it alters and refines the functional profiles of bodily actions and motor programs. I will argue that PP offers important conceptual tools and theoretical considerations that complement these basic principles of enculturation in a new and original way. The resulting account of the enculturated predictive acquisition of cognitive capacities (EPACC) has the conceptual resources to consider specific cases of cognitive development at multiple levels of explanation.

This new perspective on EPACC is a timely contribution to the debate about the philosophical implications of PP. On the one hand, Jakob Hohwy (Hohwy 2013) argues that PP implies an internalistic and neurocentric view of cognition. On his account, the embodiedness of cognitive systems and their flexible interaction with the local environment do not seem to play an important role in accounts of cognitive processes. On the other hand, Andy Clark (Clark 2016) defends the idea that PP is compatible with philosophical positions that emphasize the embodied, embedded, extended, or enacted (4E) dimensions of cognition. In this paper, I will discuss both interpretations of PP and assess their relationship to EPACC. I will challenge the internalistic account of PP on conceptual grounds. At the same time, I will argue that EPACC offers a concrete proposal for the complementarity of PP and enculturation. The overall argument is that the acquisition of new, socio-culturally shaped cognitive capacities is a matter of enculturation. The underlying neuronal and bodily transformation routines can be described in terms of PP. However, if we aim for a full-fledged account of the complexity and fragility of cognitive development, we also need an account of the fine-grained interactions of novices with their structured environment.

Keywords

Cognitive niche construction | Cognitive norms | Embodied cognition | Enculturation Neural plasticity | Neural reuse | Predictive processing | Scaffolded learning

1 Introduction

The temporally extended acquisition of cognitive capacities determines our repertoire of meaningful interactions with the world.[1] During ontogeny, we become thinkers and reasoners, learning to solve

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all kinds of problems in systematic and efficient ways. Recent work on predictive processing (PP) promises to offer an intriguing account of the neuro-functional underpinnings of cognitive development (Clark 2016; Hohwy 2013). The overall purpose of this paper is to investigate the contribution of PP to a better understanding of ontogenetic cognitive development and the acquisition of cognitive capacities.

According to PP accounts, prediction error minimization is the core principle that drives the realization of developmental changes. The revision of predictions in the light of ensuing prediction error ideally leads to a step-wise modification and refinement of future predictions at multiple levels of the hierarchically organized generative model realized in the human brain. Perceptual inference and active inference are computationally similar and highly interactive means of minimizing prediction error. In both cases, the optimization of precision estimations determines the causal influence or 'weight' of bottom-up prediction errors on the prediction error minimizing process. Precision estimations also orchestrate the relationship between perceptual inference and active inference. The minimization of prediction error and the co-occurring optimization of precision estimations are pervasive features of cognitive functioning in general. The background assumption of this paper is that there are stages of increased prediction error minimization which are associated with the acquisition of particular cognitive capacities.

For ease of exposition, I will restrict my considerations to a specific type of cognitive capacities acquired, in the majority of cases, early in life: the cognitive practices that enable the completion of complex cognitive tasks (Menary 2007; Menary 2015a; Menary 2016). Cognitive practices are embodied, socio-culturally shaped interactions with epistemic resources in the cognitive niche. The acquisition of cognitive practices is a matter of enculturation. Enculturation is a developmental process that is characterized by plastic changes to neuronal circuitry and motor profiles. It is strongly influenced by the structured interaction of an individual with its cognitive niche.

In the next section, I will briefly summarize the most important features of PP. I will then, in Section 3, consider the components necessary for the ontogenetic acquisition of cognitive capacities in terms of prediction error minimization. In Section 4, I will argue that PP, taken on its own, does not have the conceptual resources and the theoretical scope to cover the entire spectrum of components that plays a decisive role in the acquisition of cognitive practices (and most likely other kinds of cognitive capacities). I will suggest that, if we are interested in a fully-fledged description of socio-culturally structured cognitive development 'in the wild', we need to give a multi-level account of the embodied interaction of a cognitive system with its cognitive niche. In Section 5, I will relate my considerations to the emerging debate on the theoretical import of PP. In particular, I will discuss how the view to be developed here relates to Jakob Hohwy's (Hohwy 2013) and Andy Clark's (Clark 2016) interpretations of PP.

2 A Sketch of Predictive Processing

According to recently developed accounts of PP in cognitive neuroscience (Friston 2005; Friston 2010; Seth 2015) and philosophy of cognitive science (Clark 2013a; Clark 2015; Clark 2016; Hohwy 2012; Hohwy 2013; Hohwy 2015a), our engagements with the world can be best understood as a continuous attempt to minimize prediction error. On this view, perception, action, and cognition are associated with a large-scale hierarchical generative model realized in the brain. The generative model is comprised of multiple levels, each of which interacts with the next sub-ordinate and supra-ordinate level. Top-down predictions are probabilistically assessed estimations of bottom-up signals. The discrepancy between bottom-up signals and top-down predictions is the prediction error. The prediction error serves as a bottom-up signal for the next supra-ordinate level. This basic principle is iterated at multiple levels throughout the hierarchical generative model. The function of this multi-level processing mechanism is to minimize prediction error. *Prediction error minimization* can be understood as a functional attempt to reduce or explain away the difference between top-down predictions and bottom-up signals at multiple levels (Clark 2013a; Clark 2016; Hohwy 2013).

Prediction error minimization is a specific application of the *free energy principle (*Friston 2005; Hohwy 2015a; Seth 2015). According to this principle, "any self-organizing system that is at equilibrium with its environment must minimize its free energy" (Friston 2010, p. 127). Under some simplifying assumptions, we can apply this principle to cases of human perception, action, and cognition. This leads to the idea that "[f]ree energy is the sum of prediction error, which bounds the surprise of the sensory input to the system" (Hohwy 2015a, p. 2). In the present context, *surprise* is not meant to be a phenomenon that applies to the phenomenal experience of organisms as a whole at a personal level of explanation. Rather, it needs to be understood as an information-theoretic quantity — also known as *surprisal* — that is assessed at a sub-personal level of explanation *(*Hohwy 2015b). In this sense, surprisal reports "the sub-personally computed implausibility of some sensory state given a model of the world" (Clark 2013a, p. 186). It would not be computationally tractable for any system to assess surprisal directly. The solution to this tractability problem is to implicitly minimize surprisal and its upper bound — free energy — by minimizing prediction error (Hohwy 2013; Hohwy 2015a; Seth 2015). Prediction error minimization is thus a special case of a more general strategy for sustaining an organism's physiological integrity.

There are two distinct, yet highly interactive ways to minimize prediction error. In *perceptual inference*, top-down predictions are modified as a result of ensuing prediction error. In *active inference*, embodied actions bring about changes in the available sensory input so as to confirm the accuracy and adequacy of top-down predictions. On this construal, any type of bodily movement — from oculo-motor adjustments to locomotion — has the potential to confirm the best probabilistically generated predictions at multiple temporal and spatial resolutions. Perceptual inference and active inference are computationally similar, but they have a "different direction of fit" (Hohwy 2013, p. 178). They are complementary ways of minimizing prediction error. The on-going causal interaction of perceptual inference and active inference leads to the idea that they "unfold continuously and simultaneously, underlining a deep continuity between perception and action" (Seth 2015, p. 5).

Perceptual inference and active inference are orchestrated by the *optimization of precision estimations.* The degree of estimated precision determines the causal contribution of error signals to the prediction error minimization process in a given context (Clark 2014; Clark 2016). The optimization of precision estimation thus has the function of fine-tuning the influence of bottom-up prediction error signals and top-down predictions on each other in both perceptual and active inference. It has been proposed that the optimization of precision estimations is associated with the direction of *attention (*Clark 2016; Feldman and Friston 2010; Friston and Stephan 2007; Hohwy 2013). Precision estimation is considered to be equivalent to the regulation of the post-synaptic gain of specific prediction error units (Friston 2010; Feldman and Friston 2010; Hohwy 2013). The idea is that certain neurotransmitter systems (e.g., dopamine; Fletcher and Frith 2009) and neuro-modulatory hormones (e.g., oxytocin; Quattrocki and Friston 2014) are associated with post-synaptic gain control and thus with the optimization of precision expectations.

In sum, PP can be understood as a core mechanistic principle that is supposed to guide various cases of human perception, action, and cognition. A major consequence of this theoretical proposal is that we should alleviate any traditional clear-cut distinctions between these traditional mental kinds (Clark 2013a). This is because perceptual, active, and cognitive processes are all assumed to be realized by prediction error minimization.[2] On this construal, the differences between more perceptually basic and

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[2] If correct, PP has the potential to overcome traditional, unduly restrictive conceptions of the mind, which consists in the (more or less pronounced) dissociation of perceptual, active, and cognitive processes. This limitation was identified by John Dewey (Dewey 1896, p. 358) 120 years ago: "Instead of interpreting the character of sensation, idea and action from their place and function in the sensori-motor circuit, we still incline to interpret the latter from our preconceived and preformulated ideas of rigid distinctions between sensations, thoughts and acts."

more cognitively sophisticated processes, traditionally construed, would manifest themselves in the particular temporal and spatial resolution of prediction error minimization (Clark 2016; Hohwy 2013).

3 The Predictive Acquisition of Cognitive Capacities

Cognitive development falls naturally out of the basic principles that govern PP. The on-going attempt to minimize prediction error and to optimize precision estimations is nothing but a computationally tractable way of updating model parameters. Ideally, this leads to more accurate and precise sets of predictions. In this sense, prediction error minimization accounts for the developmental trajectory throughout the lifespan of perceiving, acting, and cognizing systems. This developmental trajectory is characterized by certain stages that show significantly increased levels of prediction errors and prediction revision. At these stages, novices acquire certain domain-specific capacities that allow them to interact with their local environment and to complete cognitive tasks in efficient and effective ways. Call this process of extensive and significant model updating the ontogenetic predictive acquisition of cognitive capacities (PACC). PACC temporally precedes the 'baseline' minimization of prediction error, which I dub the predictive improvement of cognitive capacities (PICC), in specific domains across the lifespan. The distinction between PACC and PICC is not clear-cut, but characterizes a continuous process that serves the general purpose of maintaining the bio-functional integrity of predictive systems. I will be primarily concerned with cases of PACC in this paper, with a particular focus on the acquisition of cognitive practices. However, it is important to bear in mind that acquired cognitive capacities, including cognitive practices, are refined and revised at multiple scales, and operate in specific contexts and situationally determined conditions across the lifespan (Clark 2016).

PACC offers a specific expression of developmental neural plasticity (Ansari 2012; Ansari 2015; Dehaene 2010; Menary 2014; Stotz 2010; Van Atteveldt and Ansari 2014) or learning driven plasticity (LDP; Menary 2015a). LDP refers to the idea that the acquisition of a certain cognitive capacity is associated with changes to the structural, functional, and effective connectivity of cortical areas.[3] LDP is not an open-ended process of resource allocation in the brain. Rather, it is constrained by anatomical properties and functional biases that define the possibility space of plastic changes in the brain (Anderson and Finlay 2014; Anderson 2015; Anderson 2016). A functional bias is defined as "a set of dispositional tendencies that capture the set of inputs to which the circuit will respond and govern the form of the resulting output" (Anderson 2015, p. 15). According to Michael Anderson's (Anderson 2015) interactive differentiation and search (IDS) framework, the functional and structural potentials of specific brain areas and local neural circuitry are exploited by a 'neural search' mechanism. The idea is that "[a] set of […] neural structures with different functional biases (different input-output mappings) would be enough to allow an ongoing process of neural search to identify and consolidate the sets of partnerships that reliably supported skills being acquired during development" (Anderson and Finlay 2014, p. 12; see also Anderson 2015). From the perspective of IDS, LDP would be about the establishment of neuronal coalitions as a result of 'neural search', which is constrained by the structural and functional properties and the connectivity potentials of cerebral units. Below, I will look at the neuronal changes associated with reading acquisition as being a paradigm example of the relation between IDS and LDP.

The IDS framework is of particular importance for our understanding of the acquisition of cognitive practices. Cognitive practices are a specific, socio-culturally shaped type of cognitive capacities. The acquisition of cognitive practices, such as reading, writing, and arithmetic augment and support the completion of certain cognitive tasks (Menary 2012; Menary 2015a). Cognitive practices are evolutionarily recent, which excludes the possibility that dedicated, exclusive, and modular neural circuitry may have emerged on a phylogenetic timescale (Anderson 2010; Anderson 2015; Dehaene 2010; Heyes 2012; Van Atteveldt and Ansari 2014). The question is how the human brain has adapted to the

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[3] For a thorough discussion of effective connectivity and its relation to PP, see Clark (Clark 2016, pp. 146-150; Clark 2013b).

processing needs afforded by recent socio-culturally shaped ways of cognizing. This includes the interaction with epistemic resources such as writing systems or number systems. A reasonable answer to this question is that global brain organization is governed by the principle of *neural reuse* (Anderson et al. 2012; Anderson 2010; Anderson 2015; Anderson 2016).

Neural reuse is defined as "the use of local regions of the brain for multiple tasks across multiple domains" (Anderson 2015, p. 4). On this view, "[…] individual pieces of the brain, from cells to regions to networks, are used and reused in a variety of circumstances, as determined by social, environmental, neurochemical, and genetic contexts" (Anderson 2015, p. 36). Dehaene's (Dehaene 2005; Dehaene 2010) *neuronal recycling* hypothesis is a specification of this principle, which is supposed to account for the cerebral realization of ontogenetically acquired cognitive practices. He defines neuronal recycling as a neuro-functionally realized "[…] form of reorientation or retraining: it transforms an ancient function, one that evolved for a specific domain in our evolutionary past, into a novel function that is more useful in the present cultural context" (Dehaene 2010, p. 146).

The combination of neuronal recycling, neural search, and the consideration of functional biases offers an account of the possibilities and constraints that determine the developmental potential of LDP for the acquisition of a certain cognitive practice. A reasonable conjecture at this point is that LDP and its guiding principles are evolutionary adaptations that allow for sufficient, yet not open-ended, flexibility in response to and in close interaction with the cognitive niche (Clark 2008; Dehaene 2010; Menary 2013; Sterelny 2003).

The PP scheme has the conceptual resources to integrate these considerations regarding LDP and the importance of neural reuse and neural search. It "[…] combines functional differentiation with multiple (pervasive and flexible) forms of informational integration" (Clark 2016, p. 150). On this construal, the principles governing LDP are realized by the ongoing minimization of prediction error in the course of PACC. Prediction error minimization is thus a means of exploiting and connecting cerebral units that are apt to contribute to the realization of a certain neuronal function.

To give an example, there is converging evidence suggesting that the left ventral occipito-temporal (vOT) area is reliably and consistently recruited in the course of reading acquisition (Dehaene 2005; Dehaene 2010; McCandliss et al. 2003; Price and Devlin 2003; Price and Devlin 2004; Vogel et al. 2013). This area has a functional bias that makes it most suitable to be reused or recycled so as to contribute to a large-scale neural circuit that is associated with visual word recognition (Dehaene 2010; Vogel et al. 2014). According to Price and Devlin's (Price and Devlin 2011, p. 248) PP account of visual word recognition, "[…] learning involves experience-dependent synaptic plasticity, which changes connection strengths and the efficiency of perceptual inference." Price and Devlin (Price and Devlin 2011) propose a three-stage model of reading acquisition in terms of prediction error minimization, with a focus on the contribution of the left vOT area to PACC. This model is the first of its kind that is able to provide an explanation for the observation that the left vOT area appears to be a hub for the development of new feed-forward *and* feed-back connections. Additionally, this model is unprecedented because it offers an account of the experimental data on the activation levels in the left vOT area across the whole trajectory of reading acquisition. The three-stage model depicts the developmental trajectory as an "inverted U-shape of activation levels" in the left vOT area and the relevant cortical areas that become increasingly functionally connected to it (Price and Devlin 2011).

At the first stage prior to the proper acquisition of reading, predictions and prediction errors associated with this cognitive practice are hardly detectable. This is because the predictive system is not yet able to identify specific task-relevant sensory signals as salient and potentially precise. At the second stage, which Price and Devlin (Price and Devlin 2011) call "early learning", prediction errors realized in the left vOT area are significantly high. This is because the top-down predictions that influence this area are inaccurate and thus are not sufficiently adjusted to the wealth of salient sensory information. The prediction error signals have a potent causal influence on supra-ordinate hierarchical levels. This normally leads to the refinement and modification of future predictions. It is at this stage that the 'neural search' mechanism is successful in the exploitation and recruitment of a cortical area that has the right kind of functional profile so as to contribute to a new, neuronal function. At the third stage, which is associated with a sufficient degree of proficiency, the relevant predictions influencing the left vOT area become increasingly accurate. Thus, they have a more pronounced causal influence on the entire processing hierarchy. Accordingly, the overall causal influence of prediction error associated with significant neuronal activation patterns in the left vOT area decreases over time.

This model of PACC is supported by converging empirical evidence on the neuronal changes that occur in the course of reading acquisition. Several neuroimaging studies suggest that the activation level of the left vOT area peaks in beginning readers and significantly decreases over time with the development of reading proficiency (Ben-Shachar et al. 2011; Brem et al. 2010; Maurer et al. 2006). In addition, it has been shown that there is a significant increase in functional connectivity between the left vOT area and higher-level left-hemispheric frontal and temporal areas that are reliably associated with visual word recognition and language processing more generally (Dehaene et al. 2010; Gaillard et al. 2003; Turkeltaub et al. 2003).

This example offers a proposal for the application of PP to concrete cases of LDP and the associated search for a cortical area that has the functional bias to contribute to a particular neuronal function. Furthermore, this example also illustrates how neuronal recycling might be realized, under the condition that prediction error minimization is a pervasive mechanistic principle that guides and refines the acquisition of new neuro-functional profiles. In this sense, PACC provides a proposal about the temporal unfolding of neural search and neuronal recycling. This is in line with Clark's (Clark 2016, p. 150) view that prediction error minimization captures the emergence of cognitive capacities in a way that is fully consistent with neural reuse and neural search: "Distinctive, objectively-identifiable, local processing organizations now emerge and operate within a larger, more integrative, framework in which those functionally differentiated populations and sub-populations are engaged and nuanced in different ways so as to serve different tasks". Importantly, this process of constrained neuronal resource allocation is modulated by the optimization of precision estimations. In particular, precision estimations determine the causal influence (or 'weight') of prediction error signals on adjacent levels of the hierarchical generative model. Clark (Clark 2016, p. 277) describes this process in the following way:

> Highly-weighted errors, if the system is unable to explain them away by recruiting some model that it already commands, result in increased plasticity and (if all goes well) the acquisition of new knowledge about the shape and nature of the distal causes responsible for the surprising inputs.

Considering our example, prediction errors realized in the left vOT area are estimated as being precise. Therefore, they have a pronounced influence on the revision and modification of supra-ordinate levels of the cortical hierarchy. This leads to the establishment of new structural, functional, and effective connections between the left vOT area and higher-level cortical areas that are equipped to generate accurate predictions. These predictions are increasingly able to meet prediction error signals driven by linguaform visual input. Given that the optimization of precision estimations is associated with attention, attention is a powerful means of altering the causal flow of predictions and prediction error signals in the course of PACC. On this construal, "[a]ttention [...] is simply one means by which certain error-unit responses are given increased weight, hence becoming more apt to drive learning and plasticity, and to engage compensatory action" (Clark 2013a, p. 190). The last point is important, because it emphasizes that both perceptual inference and active inference guide PACC.

PACC is realized by the close interaction of perceptual inference and active inference, which is constrained by the assignment of precisions to certain prediction error signals. This gives rise to the idea that LDP is complemented by a genuinely embodied component of PACC, which I call learning dependent bodily adaptability (LDBA). LDBA guides the developmental trajectory of skilled motor action in close interaction with plastic changes in the brain. The ensuing development of new motor patterns and action routines is constrained by the overall morphology of human bodies and their constitutive parts, in addition to the functional biases of cerebral regions that realize the initiation of embodied active inference.

In human vision, for example, the acuity limitations of the retina beyond the fovea constrain the emerging oculo-motor patterns displayed by proficient readers (Rayner et al. 2007; Rayner 1998; Rayner 2009). In the case of reading acquisition, eye tracking studies have revealed that these constraints lead to a characteristic profile of the alternation between saccades and fixations in the course of skill acquisition (Huestegge et al. 2009; Joseph and Liversedge 2013; Rayner et al. 2001; Seassau et al. 2013). This profile is best characterized by an efficiency gain in terms of a significant decrease of saccades, refixations, and fixation durations and a significant increase of saccade amplitudes. This efficiency gain represents the developmental trajectory of active inference in the course of PACC. Another example for the importance of bodily and motor constraints on LDBA is the anatomical and physiological organization of human hands and arms. This determines the degrees of freedom of joints and muscles, which constrain the development of movement patterns associated with writing. The physiological and mechanical properties of the involved effectors thus determine the potential characteristics of motor patterns (Alsmith 2012; Dounskaia et al. 2000; Phillips et al. 2009).

In these cases, the specific ways of embodied interaction with epistemic resources in terms of active inference are both enabled and constrained by the functional biases displayed by the anatomical and mechanic configuration of the human body. This potential for embodied active inference complements the biases of cerebral areas to contribute to the acquisition of new cognitive functions. This complementarity is orchestrated by the optimization of precision estimations. Both LDP and LDBA are thus integral components of PACC.

According to Clark's (Clark 2016) and Hohwy's (Hohwy 2013) versions of the PP framework, PACC can be seen as a specific variant of supervised learning. Hohwy (Hohwy 2013, p. 49) argues that "[t]he predictions of the internal models that determine perception are supervised by the world itself." On Clark's (Clark 2016, p. 18) view of the relationship between prediction error minimization and supervised learning, PP style accounts of learning and cognitive development (both PACC and PICC) "offer a form of self-supervised learning, in which the 'correct' response is repeatedly provided, in a kind of ongoing rolling fashion, by the environment itself." This suggests that it is the local environment that supervises the continuous process of prediction error minimization. In this way, the features and particular organization of the local environment shape and constrain the developmental trajectory of prediction error minimization and the optimization of precision.

Taken on its own, PP is primarily an account of the cerebral processes that are associated with specific instances of perception, action, cognition, and attention (traditionally conceived). Embodied active inference in the service of prediction error minimization may (Clark 2016) or may not (Hohwy 2013) serve as a reason to extend the units of analysis to include embodied interaction with the local environment. If it is the environment (or the world) which supervises learning and development, we are well advised to include the 'supervisor' and its impact on PACC into our considerations. This is where enculturation enters the picture.

4 The Enculturated Predictive Acquisition of Cognitive Capacities

Enculturation is the temporally extended transformative acquisition of embodied cognitive practices in the cognitive niche. According to proponents of enculturation, our cognitive capacities are "augmented and transformed by the acquisition of cognitive practices" (Menary 2012, p. 148). The idea of enculturated cognition commits us to the view that our understanding of the genuinely neuronal and bodily underpinnings of cognitive practices needs to be complemented by considerations of the embodied interaction of cognitive systems with their cognitive niche. The cognitive niche can be defined as the incrementally, trans-generationally structured socio-cultural environment that provides human organisms with epistemic resources for the completion of cognitive tasks. Examples of resources in the cognitive niche include tools, artefacts, and representational systems. In addition, the cognitive niche is also characterized by socio-cultural institutions like kindergartens, schools, and universities. Call this the *niche aspect* of enculturation. In addition, cognitive practices are a specific kind of "patterned practice" (Roepstorff et al. 2010), because they are shared by a large number of individuals in the socio-culturally structured cognitive niche. Therefore, the skillful performance of cognitive practices is constrained by sets of *cognitive norms* (Menary 2007; Menary 2010; Menary 2013; Menary 2015a). These norms regulate interactions with epistemic resources. They need to be learned and automatized in the course of acquisition. This is the *normative aspect* of enculturation. Since cognitive practices are socio-cultural phenomena, their acquisition is in itself a socio-culturally structured process. This process is characterized by *scaffolded learning*. In its most general form, scaffolding "denotes a broad class of physical, cognitive, and social augmentations — augmentations that allow us to achieve some goal that would otherwise be beyond us" (Clark 1997, pp. 194-195). In our context, scaffolding refers to the idea that the acquisition of a cognitive practice is a systematic process of novice-expert interaction in the cognitive niche (Menary 2013; Menary 2015a; Fabry 2015). This interaction is structured by the current developmental stage of the novice and a specific set of skills and knowledge that needs to be acquired in the long run (Estany and Martínez 2014). Call this the *scaffolding aspect* of enculturation. I will consider all three aspects of enculturation in turn.

Cognitive practices are the result of enculturation. PACC is supposed to account for the acquisition of cognitive practices. Hence, PACC should take the niche aspect, the normative aspect, and the scaffolding aspect of enculturation into account. This requires the investigation of the enculturated predictive acquisition of cognitive capacities (EPACC).

Recall from the previous section that Clark (Clark 2016) and Hohwy (Hohwy 2013) classify prediction error minimization as a specific case of supervised learning. The cognitive niche fulfills the role of a 'supervisor', enabling and facilitating the acquisition of cognitive practices. In order to be able to specify the conditions of the predictive acquisition of a certain cognitive practice, we need to take the diachronic and synchronic features and properties of the cognitive niche into account. Work on *cognitive niche construction* suggests that the trans-generational modification of the local environment has facilitated and amplified the development of increasingly fine-grained and sophisticated problem solving routines (Clark 2006; Clark 2008; Kendal 2011; Laland and O'Brien 2011; Odling-Smee and Laland 2011; Sterelny 2003; Sterelny 2012; Stotz 2010; Stotz 2014). Cognitive niche construction is further characterized by *epistemic engineering* (Menary 2014; Menary 2015a), i.e., by the principle of "organizing our physical environment in ways that enhance our information-processing capacities" (Sterelny 2012, p. xii). An important consequence of cognitive niche construction is that the phylogenetic and ontogenetic development of human cognitive capacities cannot be understood independently from considerations about the structured environment in which they are situated; we need to take the interaction and the mutual dependence of human cognitive systems and their cognitive niche into account.

In various ways, the cognitive niche assembles an abundance of *epistemic resources*, which have been shaped and reshaped in the course of cultural evolution. These epistemic resources are the product of epistemic engineering. They include but are not limited to writing systems, number systems, artefacts, and tools. Embodied interaction with these materials enables innovative and efficient solutions to cognitive challenges. These solutions are not only constrained by the overall possibilities and limitations of neuronal and bodily processing routines, but also by the properties of epistemic resources and by the principles that govern the interaction with these resources (Menary 2015a). For example, the alphabetic principle, i.e., the correspondence of specific graphemes and phonemes, constrains the ways in which cognizers can employ tokens of an alphabetic writing system in the completion of a certain cognitive task (Frith 1985; Rayner et al. 2001; Snowling 2000; Ziegler and Goswami 2006). In this sense, the exploitation of epistemic resources is governed by cognitive norms.

Cognitive norms specify the relationship between epistemic resources and the cognitive systems interacting with them. As Menary (Menary 2010, p. 229) puts it, cognitive systems are "embedded in a physical and social environment, and that environment contains norms which determine the content of environmental vehicles and how we manipulate them." Cognitive norms constrain the manipulation and interpretation of epistemic resources (Menary 2007). For example, the cognitive norm that alphabetic writing systems are spatially arranged from left to right and from top to bottom permits specific ways of interacting with a printed text and prohibits others.

Cognitive norms are acquired through scaffolded learning (Menary 2010). In the course of the acquisition of a cognitive practice, cognitive systems learn to manipulate environmental resources automatically and fluently in accordance with these cognitive norms (Menary 2013). The specific components of cognitive norms are adapted to the learner's current stage of competence. Accordingly, the "properties of cognitive norms are altered from being entirely explicit and context free to being entirely implicit and embodied" (Menary and Kirchhoff 2013, p. 9). This account of scaffolded learning is consistent with Vygotsky's (Vygotsky 1978) approach to ontogenetic cognitive development. On his view, the acquisition of a certain cognitive capacity is structured by the learner's *zone of proximal development* (Clark 1997; Menary 2007). It is defined as "the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peers" (Vygotsky 1978, p. 86; italics removed). Someone's current state of scaffolded learning is thus determined by the developmental stage of the novice and the scope and limits of her cognitive potential as defined by the zone of proximal development. This idea can also be found in the consideration of scaffolded learning by Wood, Bruner, and Ross (Wood et al. 1976). In particular, they argue that "scaffolding consists essentially of the adult 'controlling' those elements of the task that are initially beyond the learner's capacity, thus permitting him to concentrate upon and complete only those elements that are within his range of competence" (Wood et al. 1976, p. 90).

An example of the temporal unfolding of scaffolded learning is Uta Frith's (Frith 1985) influential three-stage model of reading acquisition. According to this model, the process of becoming a proficient reader is comprised of the progressive acquisition of logographic, alphabetic, and orthographic skills. At the first stage, specific words are unsystematically identified as a whole on the basis of their visual properties. At the second stage, novices are systematically trained in the application of the alphabetic principle. The emerging ability to apply grapheme-phoneme correspondence rules "is an analytic skill involving a systematic approach, namely decoding grapheme by grapheme" (Frith 1985, p. 306). Finally, orthographic skills are developed on the basis of the abilities that have been acquired at previous stages. Once alphabetic skills have reached a certain stage of automaticity and fluency, words can be recognized without explicitly associating them with their relata in spoken language.

This example emphasizes the idea that the temporal structuring of the interaction with epistemic resources is an important condition for successful enculturation. It also suggests that scaffolded learning is an inherently social process that systematically shapes the relationship between a novice and the epistemic resources located in her cognitive niche. In this sense, *path-dependent learning* is a guiding principle of scaffolded learning. Path-dependent learning induces a specific kind of "cognitive path-dependence", according to which "you can't get everywhere from anywhere, and where you are now strongly constrains your potential future intellectual trajectories" (Clark 1997, p. 205). Path-dependent learning is a process that selects and shapes the particular features of the scaffolding procedure. Clark's (Clark 1997) considerations on path-dependence develop a new twist when applied to the guiding principles of PACC:

> The hierarchical nature of the prediction-based approaches [...] makes them especially well-suited as inner mechanisms capable of supporting complex patterns of path-dependent learning in which

> later achievements build on earlier ones. At the same time, however, prior learning makes certain other regularities harder (at times impossible) to spot. (Clark 2016, p. 288)

However, the broad perspective on the acquisition of cognitive capacities I have offered so far suggests that prediction error minimization is more than just an "inner mechanism" that is apt to learn in a specific, path-dependent manner. Rather, it is in virtue of the embodied interaction of enculturated predictive systems with their cognitive niche that path-dependent learning is a potent means of EPACC. The temporally ordered and systematic exposure of scaffolded novices to structured epistemic resources, orchestrated by the optimization of precision estimations, facilitates and constrains efficient perceptual inferences and active inferences. Scaffolded learning, enacting the principle of path-dependence, is thus a good candidate for an in-depth description of the particular features of PP style supervised learning.

Taken together, all three aspects of enculturation are indispensable components of the acquisition of cognitive practices (and most likely of other types of cognitive capacities). This suggests that PACC, taken on its own, does not have the explanatory power to account for the full range of factors that contribute to the realization of cognitive practices in an important and indispensable way. The interpretation of PP advocated for here offers a plausible and epistemically rewarding "mechanism sketch" of the perceptual, active, and cognitive processes that give rise to the successful performance of cognitive practices (Piccinini and Craver 2011). This sketch is intended to be enriched by new empirical evidence for the particulars of the structural and functional realization of PP along the way (Harkness 2015). However, it does not and need not account for all components that have an indispensable impact on the acquisition of cognitive practices. We need EPACC in order to consider and describe the entire range of neuronal, bodily, and environmental components that shape and re-shape the acquisition of cognitive capacities. In this sense, the enculturation perspective and PP are complementary.

This complementarity is characterized by the "division of labour" between PP and the account of enculturation (Menary 2015b, p. 7). This becomes obvious as soon as we distinguish at least three temporal units of analysis and their association with specific levels of explanation. This is important given that enculturation is a process that unfolds in and across time (Menary 2015b). On a physiological timescale, we can attempt to provide an account of the neuronal and bodily changes that are associated with EPACC at a sub-personal level of explanation. It is here that prediction error minimization avails itself as a mechanistic proposal for the realization of LDP and LDBA.[4] On an organismic timescale, we can investigate the specific changes that characterize EPACC on a personal level of explanation. From this perspective, we can investigate the embodied interaction of human organisms with epistemic resources, the set of cognitive norms that guides this interaction, and the scaffolding procedures that facilitate the acquisition of cognitive capacities. Finally, on an evolutionary timescale, we may approach the co-ordination of the cognitive niche and the phylogenetic trajectory of human organisms at a supra-personal level of explanation.

These distinctions emphasize that the ontogenetic acquisition (and improvement) of cognitive capacities is a complex and multi-level phenomenon. But they also highlight why we should prefer EPACC over PACC: EPACC has the conceptual resources to account for the entire range of components that give rise to the acquisition of cognitive capacities. In contrast, PACC restricts itself to the specification of the neuronal and bodily underpinnings of the acquisition of a certain cognitive capacity on a physiological timescale and at a sub-personal level of explanation. From this perspective, EPACC offers a proposal for how prediction error minimization "fits within a larger account of the brain-body-niche nexus" (Menary 2015b, p. 7).

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[4] This account is markedly different from recent attempts to explain the phenomenal experience of time and temporal order in terms of PP (Friston 2016; Hohwy et al. 2016; Kiebel et al. 2008). These attempts are not interested in the temporal resolution of explanations in terms of PP per se, but rather in a PP-style explanation of the properties of temporality that characterizes our phenomenology.

5 Inside, Outside, and Beyond

EPACC speaks directly to the emerging discussion between Jakob Hohwy (Hohwy 2013) and Andy Clark (Clark 2016) about the wider theoretical ramifications of PP. In this section, I will consider how their views on PP sit with the EPACC account.

According to Hohwy (Hohwy 2013), PP commits us to thinking of cognition (traditionally conceived) in internalistic, neurocentric terms. This interpretation of PP emphasizes that "the sensory boundary between the brain and the world is not arbitrary, but rather a principled, indispensable, and epistemically critical element for identifying what is inferring what in perceptual and active inference" (Hohwy 2013, p. 240). On this construal, the "sensory boundary" separates the brain from the world in absolute terms, such that active inference and the optimization of precision estimations are nothing but functional attempts to improve the model parameters in the brain and the brain's certainty in the sensory signals it receives. The theoretical consequence is that "the mind remains secluded from the hidden causes of the world, even though we are ingenious in using culture and technology to allow us to bring these causes into sharper focus and thus facilitate how we infer to them" (Hohwy 2013, p. 239). This view, which I dub *seclusionism*, implies that the functional relevance of the embodied interaction with epistemic resources in the cognitive niche can be neglected if we try to understand the realization of cognitive processes in terms of prediction error minimization. This also applies to the developmental processes captured by the EPACC account. If "learning is just longer-term revision of hypotheses in the light of prediction error" (Hohwy 2013, p. 162), we must not consider the particular socio-cultural and bodily conditions that specify and constrain the acquisition and subsequent improvement of cognitive capacities. This is because learning would be a matter of prediction error minimization that is exclusively realized in the secluded brain. As a consequence, seclusionism is opposed to EPAAC, because EPACC emphasizes the indispensable functional role of the body and the socio-culturally shaped cognitive niche for the emergence of cognitive capacities.

Hohwy argues that "many of the ways we interact with the world in technical and cultural aspects can be characterized by attempts to make the link between the sensory input and the causes more precise (or less uncertain)" (Hohwy 2013, p. 238). On this view, the primary function of epistemic resources in the cognitive niche would be to increase the estimated precision given socio-culturally derived types of sensory input. It seems to me that Hohwy depicts the contribution of the cognitive niche to the optimization of precision estimations in relational terms. On this construal, epistemic resources would provide more precise sensory signals to the secluded brain when compared to those parts of the world that are detached from socio-cultural and technological epistemic resources.[5] This distinction between more and less precise sensory signals — based on the classification of their cultural or non-cultural causes — is hard to conceive, because human learning and cognizing are pervasively and inevitably situated in the socio-culturally structured cognitive niche. There simply does not seem to be an ecologically valid scenario under which the conceptual distinction between precise signals in the niche on the one hand and rather imprecise signals beyond the niche on the other hand would be meaningful and epistemically fruitful. Therefore, it would be highly speculative to argue that predictive systems would receive less precise sensory signals if they were detached from epistemic resources. If this is correct, learning in terms of prediction error minimization can only be understood if we take the entire "brain-body-niche nexus" into account (Menary 2015b). This is just the purpose of the EPACC approach.

Hohwy's (Hohwy 2013) idea that epistemic resources tend to increase the precision of sensory signals is questionable for another reason. The estimated precision of a prediction error signal is not fully determined by its worldly origin, e.g. by its connection to a salient aspect of a certain epistemic resource. Rather, it is determined by the *interaction* of the predictive system with that resource *across time*. For example, mathematical cognition appears to be dependent in a non-trivial sense on the tem-

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[5] Ubiquitous examples of technological resources are computers and smartphones that facilitate the completion of cognitive tasks.

porally extended embodied manipulation of mathematical symbols (Menary 2015a). Based on empirical evidence, Dutilh Novaes argues that "in typical cases manipulating portions of writing (broadly construed) is a fundamental aspect of mathematical practice" (Dutilh Novaes 2013, p. 60). In this sense, the importance of mathematical symbols would be neglected if we simply assumed that these symbols happen to provide potentially precise sensory signals. Rather, it is the on-going interaction with mathematical symbols — understood as tokens of a large-scale representational system — that brings about the completion of cognitive tasks. For this reason, I will argue that we can only understand the impact of the cognitive niche on prediction error minimization if we take the brain, the acting body, the world, and their intricate relationships into account. Vice versa, we can only understand the ubiquitous modification of the cognitive niche if we investigate the influence of embodied predictive systems on their local environment. According to the PP version of embodied action, the modification of the cognitive niche is primarily achieved by active inference, where active inference is a means of minimizing prediction error and of optimizing precision estimations. On Hohwy's (Hohwy 2013, p. 238) construal, "[t]his can generally be done by removing sources of noise in the environment and by magnifying signal strength." In these cases, active inference can only be understood if we consider its function in the context of brain-body-niche interactions (Fabry 2017). This becomes obvious when we consider the different temporal scales at which we can investigate the details of the acquisition of cognitive capacities in terms of EPACC.

On a physiological timescale, active inference is always relative to the efficiency of perceptual inference, current precision estimations, and states in the world at any given time. But the generation and execution of active inference is not only determined by the brain's current states (including the concentration of neurotransmitters in the postsynaptic gap), but also by that part of the cognitive niche that would change if an active inference were performed.

On an organismic timescale, embodied action employs and sculpts components of epistemic resources. That is, the sensory input derived from the cognitive niche is the result of previous interactions with these epistemic resources. This may explain why epistemic resources may provide precise sensory signals. Whether this kind of signal amplification applies is dependent on the particular organismic history of the predictive system's embodied interaction with specific epistemic resources. This is of particular relevance for EPACC.

Finally, on an evolutionary timescale the relationship between prediction error minimization, the evolution of the brain, the rest of the body, and the cognitive niche becomes even more intriguing. We have seen that human brains exhibit a high degree of LDP relative to functional biases and other constraints on brain functioning. We have also seen that LDP is continuous with LDBA. If the evolved primary function of the brain — in perceptual inference, active inference, and the optimization of precision estimations — were to render the sensory signals reliable and precise, it would be hard to assess how the abundance of neural reuse and the multiplicity of motor programs, cognitive resources, and institutionalized forms of scaffolded learning would have emerged during phylogeny. This potential shortcoming of seclusionism is important, because the temporal unfolding of cognitive capacities on both the organismic and the physiological scale is the result of the long phylogenetic history of humans' cognitive potential. The upshot is that we need the multi-level EPACC perspective, in addition to a non-seclusionistic interpretation of PP, if we wish to do conceptual justice to the complexity and interactive nature of our acquired and to-be-acquired cognitive capacities: "Our cognitive abilities are the result of a synergistic combination of internal neural mechanisms, bodily capacities and constraints, and environmental and social context; if we are ever to understand our brains, we must thoroughly absorb this lesson" (Anderson 2015, p. 249).

Andy Clark's (Clark 2016) interpretation of PP seems to be more compatible with this non- internalistic view of the phylogenetic and ontogenetic development of cognitive capacities. Like Hohwy (Hohwy 2013), Clark emphasizes the potentially precision-increasing role of components of the cognitive niche in prediction error minimization. On his view, "[o]rganismically salient (high precision) prediction error may thus be the all-purpose adhesive that, via its expressions in action, binds elements from brain, body, and world into temporary problem-solving wholes" (Clark 2016, p. 262). In contrast to Hohwy (Hohwy 2013), Clark (Clark 2016) emphasizes the continuity of the prediction error minimizing processes realized in the human brain with the embodied interactions with epistemic resources necessary to complete cognitive tasks. Epistemic resources are supposed to deliver precise sensory signals. According to Clark, however, this insight can only be understood when we consider the predictive brain as part of a larger unit of analysis that does not stop at the skull, but extends into the rest of the body and the cognitive niche with its unique, and often salient, properties.

In this sense, supervised learning, as it is supposed to be realized by prediction error minimization (see Section 3), needs to be understood in terms of the predictive system's enculturating interaction with the epistemic resources in its cognitive niche. As Clark (Clark 2016, pp. 276-77) puts it, "[p]rediction-driven learning routines make human minds permeable, at multiple spatial and temporal scales, to the statistical structure of the action-ready, organism-salient world, as reflected in the training signals." EPAAC provides initial considerations on the trans-temporal and multi-level features of this tight relationship between the neuronal and bodily potential of predictive cognitive systems and the cognitive niche. The 'training signals' that induce the minimization of prediction error are more than specifically precise sensory inputs to the secluded brain. On Clark's (Clark 2016, p. 171) view, "the probabilistic inference engine in the brain does not constitute a barrier between agent and world. Rather, it provides a unique tool for encountering a world of significance, populated by human affordances" (italics in original). This suggests that the continuous process of prediction error minimization does not prevent, but rather enables the skillful embodied interaction with the cognitive niche. The upshot is that we can only understand the genuinely cerebral contribution to our cognitive endeavors if we relate this contribution to the possibility landscape for embodied action delivered by the cognitive niche. In this sense, EPACC is entirely consistent with Clark's suggestion that "prediction-driven learning delivers a grip upon affordances: the possibilities for action and intervention that the environment makes available to a given agent" (Clark 2016, p. 171; italics in original). Importantly, this consideration of predictive ways of acquiring certain cognitive capacities and affordances implies that these affordances are determined by the temporally extended trajectory of the co-evolution of human organisms and their cognitive niche (Estany and Martínez 2014). This suggests a profound connection between ontogenetic and phylogenetic development of the human brain and the rest of the body on the one hand, and the unfolding of ever new epistemic resources in the cognitive niche on the other. Thus, the developmental trajectory of the genuinely cerebral processing units cannot be isolated from the on-going modification of the cognitive niche realized by embodied interactions on both organismic and evolutionary timescales.

For this reason, it is epistemically justified to include the properties of the cognitive niche into our considerations of brain functioning and the brain-body interface. These broader ramifications of PP appear to be in line with the following suggestion:

> Action and perception then work together to reduce prediction error only against the more slowly evolving backdrop of a culturally distributed process that spawns a succession of practices and designer environments whose impact on the development […] and unfolding of human thought and reason can hardly be overestimated. (Clark 2016, p. 280)

The EPACC account can be understood as a modest proposal of how we could begin to appreciate this intricate relationship. It thus offers a contribution to the emerging debate over the most suitable interpretation of the PP framework. EPACC suggests that Hohwy's (Hohwy 2013) view of the secluded predictive brain neglects the influence of the cognitive niche and bodily interaction repertoires on the phylogenetic and ontogenetic unfolding of predictive ways of acquiring and improving cognitive capacities. If seclusionism were a position that had epistemic advantages over EPACC style interpretations of PP, it would offer an argument for why we can reasonably neglect the socio-cultural conditions of genuinely human ways of completing cognitive tasks on physiological, organismic, and evolutionary timescales. Clark (Clark 2016), in contrast to Hohwy (Hohwy 2013), paves the way to interpretations of PP that take the relationship of the brain, the rest of the body, and the cognitive niche at physiological, organismic, and evolutionary timescales into account. On his view, "[t]he full potential of the prediction error minimization model of how cortical processing most fundamentally operates may thus emerge only when that story is paired with an appreciation of what immersion in a huge variety of sociocultural designer environments can do" (Clark 2016, p. 280). EPACC offers a first sketch of this relationship between prediction error minimization, embodied interaction, and the cognitive niche in the case of one of the most complex achievements of human cognition: the acquisition of cognitive practices.

6 Concluding Remarks

I have investigated how the emerging PP perspective can contribute to a better understanding of the conditions that lead to the acquisition of cognitive practices (and possibly many other types of cognitive capacities). I have suggested that PP provides us with mechanistic considerations that complement and enrich core principles of the phylogenetic and ontogenetic functional development of the brain and the rest of the body. If this line of reasoning is on the right track, it appears to be a tenable position to understand perceptual inference, active inference, and the optimization of precision estimations as a potent means to realize LDP, neural reuse, neural search, and LDBA. This idea is at the core of PACC. However, I have argued that we need to enrich PACC with a careful examination of the delicate relationship between the brain, the rest of the body, and the socio-culturally structured cognitive niche, and we need to do so across several timescales and at several levels of explanation. Therefore, consideration of enculturation and its components — especially the niche, the normative, and the scaffolding aspects — appears to be an epistemically justified complement to the descriptions offered by PACC. The core insight of EPACC is therefore that we can only understand the possibilities and limitations of human cognitive achievements if we take the entire human organism including its ongoing embodied interactions with epistemic resources in its cognitive niche into account. This insight offers a timely contribution to the emerging discussion on the ramifications of PP for our attempts to understand human cognition. In particular, EPACC reveals that we should be skeptical that the seclusionistic interpretation suggested by Hohwy (Hohwy 2013) provides us with the conceptual tools and hypotheses to allow us to account for the entire scope of the acquisition of cognitive capacities. Clark's (Clark 2016) view of predictive systems, however, seems to be more compatible with EPACC. This is because it advocates for the feasibility of considerations of cognitive growth that transcend the brain and include the rest of the body and the cognitive niche. At least as far as cognitive development and the acquisition of cognitive capacities are concerned, PP on its own may not have and need not to have the potential to cover all indispensable components that contribute to cognitive success (and failure). However, if PP is complemented by a thorough examination of enculturation and its enablers, we can begin to appreciate the possibilities and limitations of human cognition.

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