Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 March 2021 doi:10.20944/preprints202103.0540.v1

Is There a Critical Period for Second Language Acquisition? A Theoretical Social Physics Approach

ZhaoHong Han and Gang Bao
Teachers College, Columbia University
han@tc.columbia.edu
bao@tc.columbia.edu

Abstract: The critical period (CP) phenomenon in language development ranks among the 125 conundrums facing scientists in the 21st century, according to *Science*. While the phenomenon itself has been noncontroversial in first language acquisition, it still warrants an adequate explanation. Predicated on language acquisition as a complex process, questions among the first to be raised include: How do children accomplish this remarkable feat in such a short amount of time? And how do nature and nurture come together to influence language learning? In second language acquisition, however, both the notion of CP, albeit popular, and its empirical evidence have remained contested to this date - among the questions, whether the observed evidence counts as CP-specific and/or whether or not it warrants an isomorphic attribution to maturational constraints. Entwined in this debate are two well-established facets of inter-learner differential attainment. The first is that there exists a stark difference in ultimate attainment between younger and older learners. A second facet is the vast differences in ultimate attainment among older learners. In this article, adopting a social physics approach, we mathematically establish both the relationship between nature and nurture contributions and the presence of a critical period, and, at once, tender a parsimonious and probable theory for the twin phenomena of inter-learner differential attainment.

Keywords: ultimate attainment; critical period; second language acquisition; physics laws; energy conservation; angular momentum conservation; inter-learner differential attainment

INTRODUCTION

© 2021 by the author(s). Distributed under a Creative Commons CC BY license.

The Critical Period Hypothesis (CPH), as proposed by Lenneberg (1967), that language could only be successfully acquired within a finite period, extending from early infancy to puberty, has generally been taken for granted in language development research, but noticeably for first language acquisition (L1A), not for second language acquisition (L2A). Compounding the difficulty in establishing its validity in L2A are two widely observed phenomena. One, there exists a stark difference in ultimate attainment between younger and older starters. Two, there exist vast differences in ultimate attainment among older starters.

The scholarly inquiry into the two phenomena was most elegantly framed by Kellerman (1995):

> One of the enduring and fascinating problems confronting researchers of second language acquisition is whether adults can ever acquire native-like competence in a second language, or whether this is an accomplishment reserved for children who start learning at a relatively early age. As a secondary issue, there is the question of whether those rare cases of native-like success reported amongst adult learners are indeed what they seem, and if they are, how it is that such people can be successful when the vast majority are palpably not. (p. 219)

The primary question Kellerman raised here is, in essence, a critical period (CP) question, concerning differential attainment between younger and older learners, and his secondary question concerns differential attainment among older, especially adult, learners. To date, neither question has nearly been settled. Instead, the two phenomena have frequently been conflated, not the least citing one as evidence against the other. This increasingly renders a clear understanding of either phenomenon all but impossible, much less a coherent understanding of both.

We argue that an adequate understanding of complex phenomena, the CPH in L2A included, would likely surface from juxtaposing younger and older learners, and, even, of L1A and L2A. This proposition is not at all new. Academic journals, like *Applied Psycholinguistics*, *Bilingualism: Language and Cognition*, and *Language Acquisition*, have long sought to promote a holistic understanding of the nature of language acquisition. Among the researchers advocating an integrated view, Foster-Cohen (1993, 1999, 2001) has,

consistently, called for collaboration between the fields of L1A and L2A, noting that "even if the L1-L2 connections have not always been explored, most of the 'big questions' in the two fields are inherently connected" (1999, p. 4). In this article, we shall attempt connecting younger and older L2 learners in addressing the CP question.
Our point of departure is a recent theory, known as Energy Conservation in L2A (ECT-L2A; Han, Bao, & Wiita, 2017a, b), a social physics approach initially proposed as a solution to the issue of inter-learner differential attainment among adult L2 learners.

Social physics is the study of social phenomena through the lens of physics and mathematics, drawing analogues between particles and individuals (see, e.g., Wayne, 2013). Its birth dates back hundreds of years to the 17th century. The English philosopher Thomas Hobbes (1588-1679) was the first person to try to deduce what the mechanical model of the universe meant for human society. The French political philosopher Auguste Comte (1830-1842), who coined the term 'social physics,' argued in his book *System of Positive Philosophy* that "this discipline would complete the scientific description of the world that Galileo, Newton and others had begun" (1959, p. 192). A fundamental tenet of social physics is that, however obscure, unknown, or unknowable their direct causes, the play of freedom of human entails regular movement, and, thus, what seems capricious, uncertain, unpredictable, complex, chaotic, or inscrutable in the single individual's behavior is ultimately connected to underlying uniform or regular properties.

In what follows, we first provide a quick overview of the Critical Period Hypothesis research in L2A (hereafter, CPH/L2A). We then offer a précis of ECT-L2A. Next, we extend ECT-L2A to the age issue to mathematically derive the age-attainment function. After that, we discuss the resultant geometry and the fundamental nature of CPH/L2A, and, more broadly, L2 attainment across the human lifespan. By way of conclusion, we proffer some thoughts on how ECT-L2A can be further substantiated.

Before proceeding, however, it is important that we set two perimeters, both appearing to be sources of confusion and ambiguity in the CPH/L2A research. The first is that the linguistic domain in which we theorize interlearner differential attainment concerns only the grammatical/computational aspects of language, or what Hulstijn (2015, 2019) calls basic language cognition – aspects of language where native speakers show little variance. The second is that we are concerned only with natural acquisition, not instructed learning.

THE CRITICAL PERIOD HYPOTHESIS IN L2A

To date, two questions have dominated the research on CPH/L2A: *What counts as evidence of a critical period*? *What accounts for the age-attainment difference between younger and older learners?*

More than four decades of research on CPH/L2A - from Oyama (1976) to Johnson and Newport (1989) to Hartshorne, Tenenbaum and Pinker (2018) - have, in the main, pointed to an inverse correlation between the age of acquisition (AoA) and the level of grammatical attainment (see also Abrahamsson, 2012; DeKeyser, 2000, 2012; DeKeyser, Alfi-Shabtay, & Ravid, 2010; Grenena & Long, 2013; Hyltenstam & Abrahamsson, 2003; Jia & Fuse, 2007; Long, 1990, 2005, 2007; Mayberry & Lock, 2003; Meisel, 2009, 2013; Oyama, 1976; Patkowski, 1980; Pinker, 1994; Schachter, 1996; Scovel, 2000; Qureshi, 2016). However, views are almost orthogonal over whether the observed inverse correlation can count as evidence of the CPH or the observed difference is non-maturationally related (see, e.g., Birdsong, 1999, 2006, 2009, 2018; Birdsong & Molis, 2001; Bialystok & Hakuta, 1999; Bialystok & Miller, 1999; Bialystok & Kroll, 2018; Hakuta, Bialystok & Wiley, 2013; Herschensohn, 2007; Marinova-Todd, Marshall, & Snow, 2000; Muñoz & Singleton, 2010; Singleton, 2001; White & Genesee, 1996).

To some, true evidence or falsification of CPH/L2A must be tied to the level of attainment of late learners, that is, whether or not they can attain nativelikeness (e.g., Long, 1990). Others, however, contend that nativelikeness itself is a problematic construct for L2A, due to the fact that monolingual-like native attainment for L2 learners – who amount to sequential bilinguals - is out of the question (Cook, 1992; Grosjean, 1989). Echoing this view, Birdsong (2005a) argued:

> Bilinguals are not “two monolinguals in one” in any social, psycholinguistic, or cognitive neurofunctional sense. From this perspective, it is of questionable methodological value to quantify bilinguals’ linguistic attainment as a proportion of monolinguals’ attainment, with those bilinguals reaching 100% levels of attainment considered nativelike. (p. 121)

Empirical research focusing on late L2 learners have, in the main, reported *selective* nativelike attainment, that is, in some aspects but not in others. These studies employed a variety of methodologies, including group and case studies (see, e.g., Birdsong, 1992; Coppieters, 1987; Donaldson, 2011, 2012; Ioup *et al*, 1994; Franceschina, 2005; Han, 2006, 2010, 2014; Hopp, 2010, 2013; Lardiere, 2007; Saito, 2015; Sorace, 1993; van Boxtel, 2005; White & Genesee, 1996; Yuan & Dugarova, 2012). For some but by no means for all, the selective nativelikeness constitutes falsifying evidence of CPH/L2A.

Circumventing the fraught nature of nativelikeness, Birdsong (2005b) argued that CPH/L2A must ultimately be subjected to geometric tests: if studies comparing younger and older learners yield the geometry of a "stretched *Z*" for the age-attainment function, that would prove the validity of CPH/L2A, or falsify it, if otherwise.

The stretched *Z* or inverted *S* (DeKeyser & Larson-Hall, 2005) derives from the interpretation of the CPH as positing a bounded period in which the organism exhibits heightened neural plasticity and sensitivity to linguistic stimuli in the environment. This period has certain temporal and geometric features. Temporally, it extends from early infancy until puberty, coinciding with the time during which the brain undergoes maturation (Lenneberg, 1967; Long, 1990; Pinker, 1994; Pulvermüller & Schumann, 1994; Scovel, 1988). Geometrically, this period "typically shows an abrupt onset or increase of sensitivity, a plateau of peak sensitivity, followed by a gradual offset or decline, with subsequent flattening of the degree of sensitivity" (Birdsong 2005b, p. 111), evoking the shape of a stretched *Z*.

By these temporal and geometric hallmarks, few available empirical studies actually confirmed CPH/L2A, not even those that reportedly offered stark evidence. A case in point is the seminal study by Johnson and Newport (1989), the first study claiming to have found clear-cut evidence of CPH/L2A (r=-.87, p<.01 for the early age of arrival (AoA) group; r=-.16, p>.05 for the late AoA group). Johnson and Newport offered that "test performance was linearly related to [AoA] up to puberty; after puberty, performance was low but highly variable and unrelated to [AoA]," which supports "the conclusion that a critical period for language acquisition extends its effects to second language acquisition" (p. 60).

But for some, the results of the Johnson and Newport study did not fully match the stretched *Z*. Birdsong (2005b), for instance, pointed out that the random distribution of test scores

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 March 2021 doi:10.20944/preprints202103.0540.v1

within the late AoA group "does not license the conclusion that 'through adulthood the function is low and flat' or the corresponding interpretation that 'the shape of the function thus supports the claim that the effects of age of acquisition are effects of the maturational state of the learner'(Johnson & Newport, 1989, p. 79)" (p. 117). He added that if the CPH obtains in L2A, the performance scores of the late AoA group should be distributed horizontally in addition to showing marginal correlation with age. Accordingly, the random distribution of scores could only be taken as indicative of "a lack of systematic relationship between the performance and the AoA and not of a 'levelling off of ultimate performance among those exposed to the language after puberty' (Johnson & Newport, 1989, p. 79)" (Birdsong, 2005b, p. 118).

Interpreting the same study, other researchers, such as DeKeyser and Larsen-Fall (2005), notably set their sights not as much on the random distribution of the performance scores as on the discontinuity between the early AoA and late AoA groups, arguing that the qualitative difference is sufficient evidence of CPH/L2A.

If geometric satisfaction is one flash point in CPH/L2A research, explaining random distribution of performance scores or, essentially, differential attainment among late learners is yet another. Studies analyzing late learners' ultimate attainment (e.g., Abrahamsson, 2012; Abrahamsson & Hyltenstam, 2008; Bialystok & Hakuta, 1999; Bialystok & Miller, 1999; Birdsong & Molis, 2001; DeKeyser, 2000; White & Genesee, 1996) have uncovered a host of cognitive, social-psychological, or experiential factors that appear to partake of inter-learner differential attainment. The question, then, is whether these non-age factors reinforce or supplant the age or maturational effect.

These are complex issues that require sophisticated solutions beyond methodological repairs, a common recommendation by many (see, e.g., Granena & Long, 2013; Qureshi, 2016). It is possible that future studies building off of methodological insights from previous studies will expand on current findings, but it is just as likely that they further 'muddy the water,' for the simple reason that methodology is at best a contingent factor interplaying with a variety of other factors - subjects, setting, linguistic domains and subsystems, duration of study, to name but a few. A three-way comparison, for instance, of DeKeyser (2000), Abrahamsson and Hyltenstam (2008), and Granena and Long (2013) would shed tangible light on methodological idiosyncrasies and evidential differences over two shared denominators, AoA

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 March 2021 doi:10.20944/preprints202103.0540.v1

and aptitude and on how they, then, led to similar and different understandings of CPH/L2A. In the remainder of this article, we take a different tack to the age issue, adopting a L2A instantiation of a theoretical social physics approach, known as Energy Conservation Theory for L2A (ECT-L2A; Han, Bao & Wiita, 2017a, b). We mathematically demonstrate that ECT-L2A is capable of resolving the twin facets of interlearner differential attainment.

WHAT IS ECT-L2A?

ECT-L2A (Han, Bao & Wiita, 2017a, b) is a social physics theory of L2 ultimate attainment. Drawing on the universal laws of energy conservation and angular momentum conservation,[1] it theorizes the dynamic transformation and conservation of internal and external energies, which, in turn, derive from the interaction between nature and nurture factors – the linguistic environment, learner motivation, learner aptitude, distance between L1 and target language (TL) and the developing learner. External energies, in this case, originate from the central source of a gravitational field or the ambient TL, and internal energies come from the learner.

ECT-L2A draws a number of parallels between mechanical energies and human learning energies:[2] kinetic energy for motivation and aptitude energy, potential energy for environmental energy, and centrifugal energy for L1-TL deviation energy. These energies each perform a unique role and yet they convert from one type to another, as the learner progresses in the developmental process, with the total energy remaining constant, as per the Law of Energy Conservation, according to which energy cannot be created or destroyed, but it can be converted from one type to another, without changing the total amount of energy.

---

[1] The learning phenomenon in question, *differential attainment in L2A*, aligns well with that of an object moving in a gravitational field toward its central source, like an object moving around a black hole, constrained by the laws of energy conservation and angular momentum conservation.

[2] The reader may wonder about the parallels, especially about the extension of the term 'energy' to humans. Our basic assumption is that, if energy is, by definition, what drives a change of state, it should be capable of changing a cognitive state, just as it can change a physical state. In fact, we are not the first to posit that the concept of energy extends from the physical world to humans. For example, Loehr and Schwartz (2005), the authors of *The Power of Full Management*, a Wall Street Journal and New York Times bestseller which has been translated into 28 languages, have noted: "Human beings are complex energy systems. The energy that pulses through us is physical, emotional, mental, and spiritual. All four dynamics are critical, none is sufficient by itself and each profoundly influences the others" (p. 9).

Mathematically, ECT-L2A reads as follows:

$$\epsilon = \zeta(r) + \Lambda + \frac{\eta^2}{r^2} - \frac{\rho}{r} \qquad (1)$$

where $\zeta(r)$ denotes the learner's motivation, *r* the learner's location in the learning process relative to the TL, η the distance between L1 and TL, and ρ the 'mass' of TL.

Expressed in Equation (1) is that the total learning energy, ϵ, comes from the sum of motivation energy $\zeta(r)$, aptitude (a constant) Λ, deviation energy $\frac{\eta^2}{r^2}$, and environmental energy - $\frac{\rho}{r}$, where *r* refers to the learning process marked by an onset and an offset, as shown in Figure 1.

Under the overarching condition of total energy $\epsilon = constant$, each type of energy performs a different role, with one converting to another, as the position of the learner changes in the developmental process. The expression of each energy type must not be random, for example, $\frac{\eta\epsilon^3}{r^3}$ or $\frac{\rho^5}{r^2}$; instead, they must be expressed exactly as in Equation (1), determined by the nature of the gravitational field (see e.g. Rogalski & Palmer, 2006).

The energy types included in Equation (1) embody both nature and nurture influences. The potential energy or TL traction, - $\frac{\rho}{r}$, represents environmental influence, while the kinetic or motivational energy, $\zeta(r)$, along with aptitude, Λ, and the centrifugal or deviation energy, $\frac{\eta^2}{r^2}$, represent internal influences.

For mathematical and conceptual convenience, (1) is rewritten into (2) which contains the effective potential energy, $U_{eff}(r)$.

$$\epsilon = \zeta(r) + \Lambda + U_{eff}(r) \qquad (2)$$

where $U_{eff}(r) = \frac{\eta^2}{r^2} - \frac{\rho}{r}$. As such, the effective potential energy combines opposing energies, in the present case, the sum of the deviation energy and the potential energy of the system.

While the total energy varies from learner to learner, it is constant for a given L2 learner. Consequently, different learners can arrive at different levels of ultimate attainment (i.e., closer or more distant from the TL), r_0, as shown in Figure 1, where r_0 and r'_0 indicate ultimate attainments for learners with different amounts of total energy, $\epsilon>0$ and $\epsilon<0$.

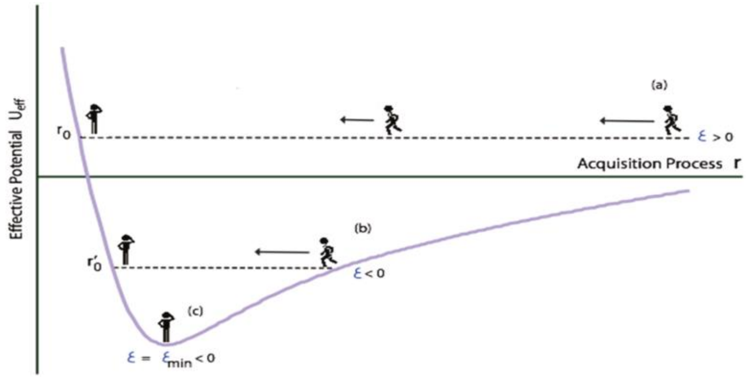

Fig. 1: Inter-learner differential ultimate attainment as a function of different amounts of total energy: $\epsilon>0$; $\epsilon < 0$; $\epsilon = \epsilon_{min}$ (Han, Bao, & Wiita, 2017a, b)

Important to understanding Figure 1 is that it is the individual's total energy that determines his or her learning trajectory. Of the three scenarios displayed here, ECT-L2A is only concerned with the case of $\epsilon \geq 0$, which represents the unbound process (r_0, ∞), ignoring the bounded processes of $\epsilon < 0$; $\epsilon = \epsilon_{min}$.

The central thesis of ECT-L2A, as expressed in Equation (1), is that the moment a learner begins to receive substantive exposure to the TL, s/he enters a 'gravitational' field or a developmental ecosystem in which s/he is initially driven by kinetic or motivational energy, increasingly subject to the traction of the environmental energy (i.e., TL input), but ultimately stalled by the deviation energy. A further elaboration follows.

Initially (i.e., when the learner is at infinity, $r = \infty$), his or her progression toward the central source, i.e., the TL, is driven almost entirely by his or her motivation energy and aptitude, as expressed in Equation (2).

$$\epsilon = \zeta(\infty) + \Lambda \qquad (2)$$

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 March 2021 doi:10.20944/preprints202103.0540.v1

As learning proceeds, but with r still large (i.e., the learner still distant from the target) and the deviation energy much weaker than the environmental energy, $\frac{\eta^2}{r^2} \ll \frac{\rho}{r}$ (due to the second power of r), the motivation energy rises as a result of its interaction with the environmental energy $-\frac{\rho}{r}$, meaning that more environmental energy is giving way to the motivation energy (see the minus sign of the environmental energy). Mathematically, this is expressed in Equation (3).

$$\epsilon \approx \zeta(r) + \Lambda - \frac{\rho}{r} \qquad (3)$$

However, as learning further progresses, the environmental energy begins to dominate until it then yields to the influence of deviation energy, $\frac{\eta^2}{r^2}$, which exerts increasing power over the learner. Eventually, the deviation energy outweighs the influence of the environmental energy, as expressed in Equation (1), repeated below as (4) for convenience.

$$\epsilon = \zeta(r) + \Lambda + \frac{\eta^2}{r^2} - \frac{\rho}{r} \qquad (4)$$

The deviation energy is so powerful that it eclipses all other types of energy, effectively drawing the learner away from the target and stalling him or her at asymptote, where their motivation energy becomes minimal, $\zeta(r_0) = 0$, as expressed in (5).

$$\epsilon = \Lambda + \frac{\eta^2}{r_0^2} - \frac{\rho}{r_0} \qquad (5)$$

Thus, according to ECT-L2A, the deviation energy is what ultimately determines the learner's level of attainment. At this stage, all of the initial motivation energy $\zeta(\infty)$ is converted to the deviation energy and some of the gravitational energy is converted to it as well. In other words, further exposure to TL input is of no substantive help.

Figure 2 gives a geometric description of the L1-TL deviation η, which is similar to the angular momentum of an object moving in a central force field (Bao, Hadrava, & Ostgaard, 1994a, b; Bao, Wiita, & Hadrava, 1996). The deviation from the TL, otherwise known as the distance between the L1 and the TL, varies with different L1-TL pairings. For example, the distance index, according to the Automated Similarity Judgment Program Database (Wichmann, Holman & Brown, 2016), is 90.25 for Italian and English but 100.33 for Italian and Chinese.

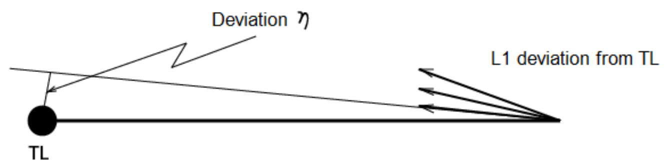

Fig. 2: Geometric description of the deviation parameter η

Figure 3 illustrates differential ultimate attainment (indicated by r_0) as a function of the deviation parameter η **.** As η increases, the attainment is lower or further away from the target (where r_0=0).

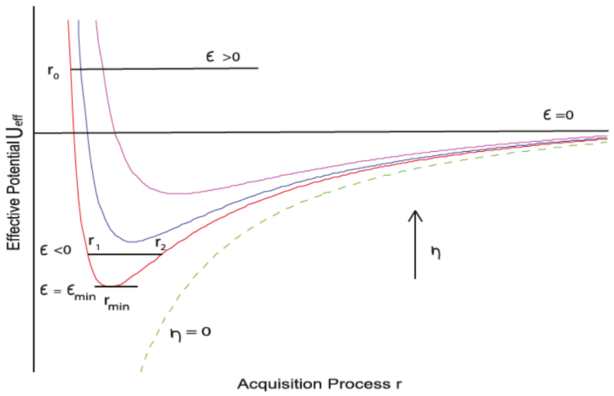

Fig. 3: Effective potentials U_{eff} with different values of η (Han et al., 2017a, b)

ECT-L2A predicts, for adult L2A, that high attainment is possible but full attainment is not. It also predicts that while motivation and aptitude are part and parcel of the total energy of a learner, its role is largely confined to the early stage of development. Most of all, ECT-L2A predicts that *deviation energy is what ultimately keeps an adult learner at asymptote*. In the next section, we mathematically extend ECT-L2A to the critical period issue.

EXTENDNG ECT-L2A TO THE CRITICAL PERIOD

Following from ECT-L2A, as long as η (i.e., L1-TL distance) is non-zero, the learner's ultimate attainment, r_0, will always wind up in an asymptote. As shown in Figure 3, the larger the deviation η, the more distant the r_0 is from the TL. Put differently, a larger η portends that learning will reach an asymptote earlier or that the ultimate attainment will be less target-like. But how does that work for child L2A?

The "younger is better" phenomenon is widely observed. Anecdotal observations alone, especially of immigrant families, unambiguously attest to a markedly different outcome for L2A by young learners, an outcome that is both reliable and convergent (Bley-Vroman, 2009). Experimental research has largely corroborated the observations, showing, *inter alia*, that "the age of acquisition is strongly negatively correlated with ultimate second language proficiency for grammar as well as for pronunciation" (DeKeyser & Larson-Hall, 2005, p. 88). Environmental differences, as in input exposure, though often invoked as a key factor, do not seem to adequately account for this phenomenon. Granena and Long (2013), for example, argued:

> [R]estricted input cannot explain the high levels of achievement, but non-nativelike achievement, attained by the many non-native speakers (NNSs) who live in the L2 environment for decades, often married to native speakers (NSs) of the L2, who use the L2 both at work and in almost every aspect of their social lives, and who exhibit no attitudinal or motivational barriers to acquisition. (p. 312)

Still, what causes the superior learning of young learners is less clear and has remained a subject of intense debate (see, e.g., Birdsong, 2018; Long, 2005; MacWhinney, 2006). As noted earlier, Lenneberg's CPH identifies maturation as the underlying mechanism. "There is something special about the maturational state of the child's brain which makes children particularly adept at acquiring any language, first as well as second. … language learning abilities decline with maturation" (Newport, 1991, p. 64). Yet, a lingering challenge for this account has been to tie specific neurological changes to language learning abilities (Birdsong, 2005b; DeKeyser, 2012; DeKeyser & Larson-Hall, 2005). This challenge is significantly alleviated by ECT-L2A.

On the ECT-L2A account, it is the low η value that determines child learners' superior attainment. In child L2 learners, the deviation is low, because of the incipient and underdeveloped L1. However, as the L1 develops, the η value grows until it becomes a constant, presumably happening around puberty.

As noted and shown in figures 1 and 3 (where r_0 indicates ultimate attainment), the smaller the deviation, η, the closer r_0 is to the TL or the higher the ultimate attainment.

From Equation (5) the ultimate attainment of an L2 learner can be mathematically derived, as in (6).

$$r_o = \frac{2\eta^2}{\rho + \sqrt{4\varepsilon\eta^2 + \rho^2}} \qquad (6)$$

where $\varepsilon = \epsilon - \Lambda$. r_0 here represents the distance between the target and the closest point a learner can reach. Note that a solution where $r_0 < 0$ is meaningless and hence not considered here. The geometry of ultimate attainment as a function of deviation, η, is displayed in Figure 4a.

For a given child learner, η is a constant, but *different child learners can have a different* η *value, depending on the timing of onset of his or her L2 learning*. This underpins a crucial difference from adult learning where η is a constant for *all* learners because of their uniform late onset of learning when, as noted above, the deviation between their L1 and the TL has already saturated or reached its maximum (see Fig. 4b). Simply put, the L1 of an adult learner has fully developed, unlike that of a child learner which is developing.

Further to the ECT-L2A argumentation, when η varies across different child L2 learners, it is alternatively a function of L2 age of acquisition (AoA) or time (t), which can be expressed as $\eta(t)$, a *deviation function of time*. It varies in the range of $0 \leq \eta(t) \leq \eta_{max}$. Thus, Equation (6) can be mathematically rewritten into (7):

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 March 2021 doi:10.20944/preprints202103.0540.v1

$$r_o\ (t) = \frac{2\eta(t)^2}{\rho + \sqrt{4\varepsilon\eta(t)^2 + \rho^2}} \qquad (7)$$

Assuming that as *t* grows or as AoA advances, η increases slowly and smoothly from 0 to η_{max} until it solidifies into a constant, which marks the onset of adult learning, accordingly $\eta(t)$ can mathematically be expressed as (8).

$$\eta(t) = \frac{\eta_{max}}{\pi}[arctg(t - a) + \pi/2] \qquad (8)$$

where a is a constant. The geometry of the deviation function of time is displayed in Figure 4b.

Figures 4a and 4b illustrate *a double non-linearity* characterizing L2 acquisition by young learners: first, with ultimate attainment a function of deviation (Equation 6), and, second, with deviation a function of AoA (Equation 8).

Figure 4a displays the first order of nonlinearity of $r_0(\eta)$, that is, ultimate attainment as a function of deviation or the L1-TL distance. Figure 4b displays the second order of nonlinearity, η(t), that is, η changes with *t*, age of acquisition (AoA).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 March 2021 doi:10.20944/preprints202103.0540.v1

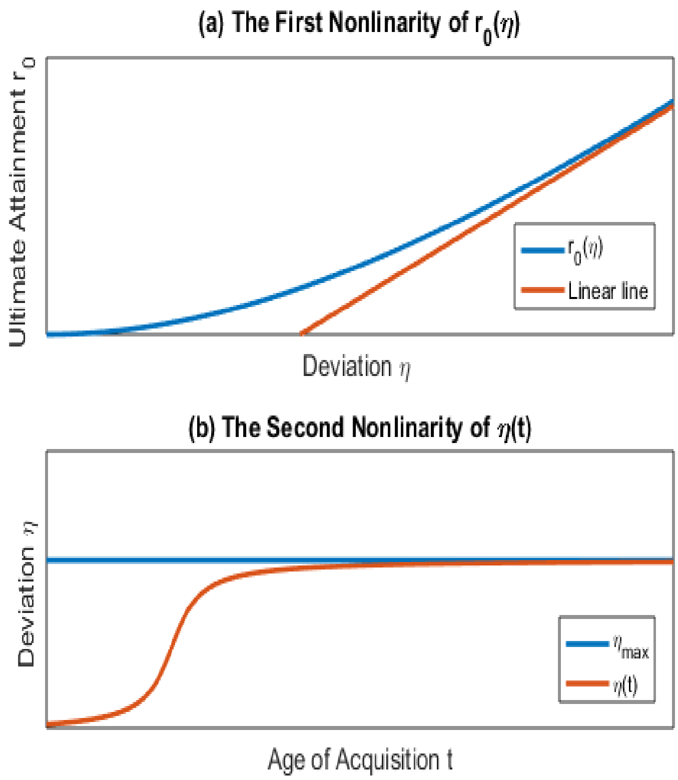

Fig 4: Double non-linearity of $r_0(\eta)$ and $\eta(t)$ at early AoA

Important to note here is the timing of the double non-linearity: both occur during early AoA.

Figure 5 illustrates ultimate attainment (the blue line) as a function of AoA, $r_0(t)$, and its derivative against *t* (the orange line),[3] $\frac{dr_0}{dt}$, which *naturally* yields three distinctive periods: the critical period, $t_{critical}$; the post-critical period, $t_{p\_critical}$; and the adult learning period, t_{adult}. Within the critical period, $t_{critical}$, $r_0 \cong 0$, meaning there is no difference in attainment as age of acquisition increases. Within the post-critical period, $t_{p\_critical}$, r_0 changes dramatically, with $\frac{dr_0}{dt}$ peaking and waning until it drops to the level approximating that of adult learners. Within the adult period, t_{adult}, r_0 remains a constant, as attainment levels off.

[3] In mathematics, derivatives are a fundamental tool of calculus. In the present context, the derivative of the function r_0 of the variable *t* measures the sensitivity to change of r_0 with respect to change in *t*.

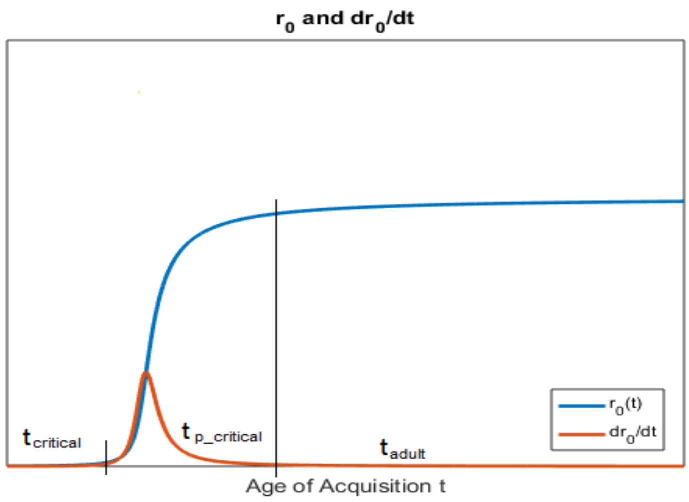

Fig. 5 Ultimate attainment (the blue line) as a function of age of acquisition (*t*) and its derivatives giving three distinctive periods (the orange line)

ECT-L2A, thus, predicts three learning periods. First, there is a critical period, $t_{critical}$, within which attainment is nativelike, $r_0 \cong 0$. Notice that the blue line is the lowest during the critical period, signifying that attainment converges on the target, but it is the highest during the adult period, meaning that attainment diverges greatly from the target. The offset of the critical period is smooth rather than abrupt, with the impact of deviation, η, slowly emerging at its offset. During this period, the L1 is surfacing, with negligible deviation from the TL. Key to understanding this account of the critical period is the double non-linearity: first, ultimate attainment is a function of L1-TL deviation ($r_0(\eta)$, see Fig. 4a); and second, L1-TL deviation is a function of AoA ($\eta(t)$; see Fig. 4b). Crucially, *this double non-linearity extends a critical 'point' into a critical 'period'*.

According to ECT-L2A, there is a post-critical period, $t_{p\_critical}$, $0 < r_0 \leq r_0(\eta_{max})$, within which, with advancing AoA, the deviation (i.e., L1-TL distance) grows larger, resulting in ultimate attainment that is increasingly lower (i.e., increasingly non-targetlike). The change rate of r_0, its first derivative to time, $\frac{dr_0}{dt}$, is dramatic, waxing and waning. As such, the post-critical period is more complex and nuanced than the critical period. During the post-critical period, as the learner's L1 becomes increasingly robust and developed, the deviation becomes larger and the L2 attainment further away from the target (i.e., increasingly non-targetlike).

ECT-L2A predicts a third period called the adult learning period, t_{adult}, $\eta = \eta_{max} \cong constant$, where, despite the continuously advancing AoA, the deviation reaches its maximum and remains a constant, as benchmarked in indexes of crosslinguistic distance (see, e.g., the Automated Similarity Judgment Program Database, Wichmann, Holman & Brown, 2016). As a result, the L2 development turns asymptotic (for discussion, see Han et al., 2017a, b).

Confirming the putative geometry of the critical period

ECT-L2A identifies η as the determinant of age effects in L2A and the double non-linearities, $r_0(\eta)$ (Fig. 4a) and $\eta(t)$ (Fig. 4b), as underlying the critical period. Ultimate attainment is, accordingly, the highest during the critical period, high during the post-critical period, and low during the adult learning period. The resultant geometry is a stretched Z, the slope, according to some (Birdsong, 2005b; Pinker, 1994; Johnson & Newport, 1989), unequivocally supporting CPH/L2A and thus implicating maturation as the biological mechanism for the generally high versus low L2 proficiency in early and late starters. “[T]he stretched Z representation serves as a basis for contrasts with other age functions that do *not* exemplify features of a critical period” (Birdsong, 2005b, p. 113).

For better illustration, we can convert Figure 5 into Figure 6, using Equation (9).

$$a_{tt} = \frac{1}{r_0 + \frac{1}{a_{tt(\max)}}} \qquad (9)$$

where a_{tt} stands for level of attainment. According to Equation (9), the smaller the r_0, the higher the attainment.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 March 2021 doi:10.20944/preprints202103.0540.v1

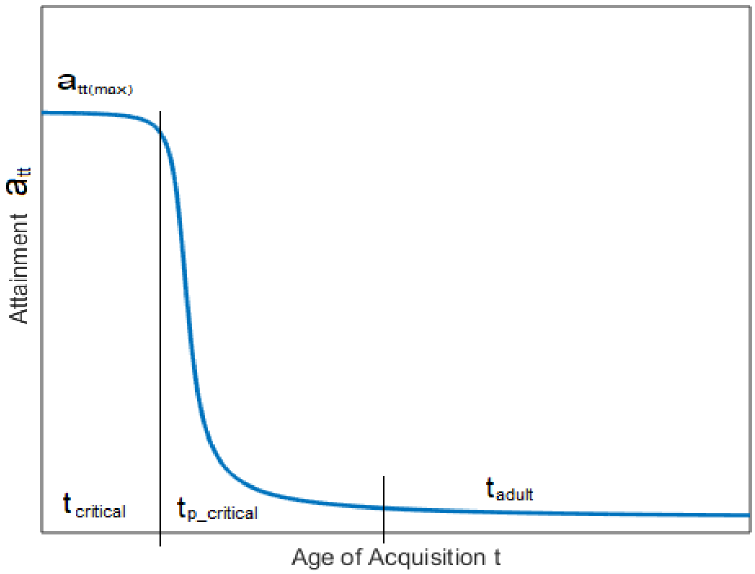

Fig. 6: Level of attainment as a function of AoA

Reviewing available empirical research on CPH/L2A, Birdsong (2005b) found that few studies produced findings matching the geometry of a stretched *Z*. He thereby concluded that "the construct of a critical period is a poor fit for SLA age effect data" (p. 109). But then, he identified methodological variability across the studies, such as the types of statistical analysis adopted, as a major threat to the reliability of the findings (see also DeKeyser & Larson-Hall, 2005; Qureshi, 2016). As mentioned earlier, we believe that methodological repairs may reasonably help expand the empirical findings but may not necessarily lead to a better understanding of CPH/L2A. ECT-L2A, theoretically, fills the void, mathematically establishing the critical period geometry: "there is an abrupt onset or increase of sensitivity, a plateau of peak sensitivity, followed by a gradual offset or decline, with subsequent flattening of the degree of sensitivity" (Birdsong, 2005b, p. 111).

It is worth pointing out, however, that there is a discrepancy between the ECT-L2A designation of the critical period and that of Birdsong (2005b), who argued that "the span of a critical period is properly understood as beginning at the moment when sensitivity starts to increase and ending at the point at which sensitivity is at its lowest level" (p. 111). This conception lumps into one period what ECT-L2A has mathematically identified as two distinct periods: the critical period and the post-critical period. We believe that a more

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 March 2021 doi:10.20944/preprints202103.0540.v1

stringent definition of the critical period can be heuristically richer, a point to which we will return.

Explaining CPH/L2A

On the ECT-L2A account of the critical period, η (i.e, L1-TL deviation) is considered an inter-learner variable and, at once, a proxy for age of acquisition, t. But, underlyingly, η is connected to neural plasticity or sensitivity (cf. MacWhinney, 2006). The relationship between plasticity, $p\ (t)$, and deviation function, $\eta\ (t)$, can be expressed as (10):

$$p\ (t) = \frac{1}{\eta\ (t) + \frac{1}{p_{max}}} \qquad (10)$$

The relationship is, thus, one of inverse correlation. During the critical period, $\eta = \eta_{min}$ (i.e., minimal L1-TL deviation) and $p = p_{max}$ (i.e., maximal plasticity); conversely, during the adult learning period, $\eta = \eta_{max}$ (i.e., maximal L1-TL deviation) and $p = p_{min}$ (i.e., minimal plasticity). In short, an increased deviation, $\eta\ (t)$, corresponds to a decreased plasticity, $p\ (t)$, and vice versa, as illustrated in Figure 7.

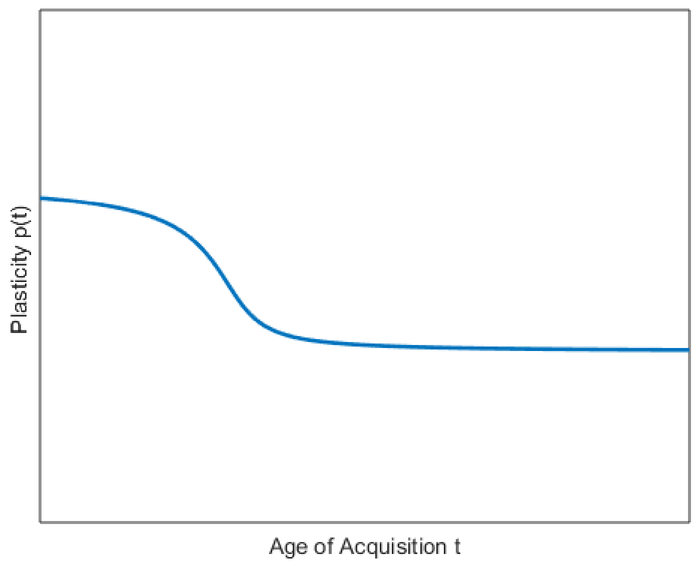

Fig 7: Plasticity as a function of age of acquisition

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 March 2021 doi:10.20944/preprints202103.0540.v1

Neural plasticity, first proposed by Penfield and Roberts (1959) as the underlying cause of CP, is at its highest during the critical period (cf. Wartenburger *et al*., 2003), and, as Bornstein (1989) put it, it "endures within the confines of its onset and offset" (p. 182). But it begins to decline and drops to a low level during the post-critical period, and remains low through the adult learning period. Accordingly, it makes sense to call the first period "critical" and the second period "sensitive." The post-critical period or the sensitive period has received scant empirical attention in CPH/L2A research, though it should be just as relevant, if not as important, as either the critical or the adult period, to understanding the role of brain maturation in L2A. Temporally, following Pinker's (1994) conjecture, the critical period should last through early childhood from birth to age six, and the sensitive period should offset around puberty (see also DeKeyser & Larsen-Hall, 2005; Grenena & Long, 2013; Hyltenstam & Abrahamsson, 2003; Long, 1990). Importantly, both periods are circumscribed, exhibiting discontinuities, with the critical period exhibiting maximal sensitivity, the sensitive period declining, though, for the most part, still far greater, sensitivity than the adult learning period.

This view of a changing underlying mechanism across the three periods of AoA and attainment resonates with the Language as a Complex Adaptive System perspective (see, e.g., Larsen-Freeman, 2020). Elman (2003), for example, noted that "the processing mechanisms that underlie [language development] … are fundamentally nonlinear. This means that development itself will frequently have phase-like characteristics, that there may be periods of extreme sensitivity to input ('critical periods')" (p. 431).

ECT-L2A PROVIDING A UNIFYING EXPLANATION

On ECT-L2A, the L1-TL deviation, η, serves as a lynchpin that unites both an explanation of ultimate attainment difference between early and late starters, one the one hand, and among late starters, on the other. In early AoA, the deviation is an inter-learner variable as well as a temporal and neuro-functional proxy tied to a developing L1 and at once to changing age and plasticity. In contrast, in late AoA, η is a constant, due to the L1 being fully developed and the brain fully mature. Johnson and Newport (1989: 89) had this to say about late L2A:

> If the explanation for late learners' poor performance relates to maturation, performance should not continue to decline over age because presumably

> there are not many important maturational differences between, for example, the brain of a 17-year-old and the brain of a 27-year-old. Instead, there should be a consistent decline in performance over age for those exposed to the language before puberty, but no systematic relationship to age of exposure, and a leveling off of ultimate attainment among those exposed to the language after puberty.

Indeed, empirical research on late learners has consistently reported differential attainment (see, e.g., Birdsong, 1992; Coppieters, 1987; Donaldson, 2011, 2012; Ioup *et al*, 1994; Franceschina, 2005; Han, 2006, 2010, 2014; Hopp, 2010, 2013; Lardiere, 2007; Saito, 2015; Sorace, 1993; Stam, 2015; White & Genesee, 1996; Yuan & Dugarova, 2012), a finding which many have taken as falsifying evidence of CPH/L2A, pointing, in particular, to instances of selective nativelike attainment, a criterion that has itself come under scrutiny in L2A research (see, e.g., Abrahamsson & Hyltenstam, 2009; Birdsong, 2005a, 2018; Cook, 1992; DeKeyser, 2012; Grosjean, 1989).

What, then, accounts for the inter-learner differential attainment among late learners? The answers allegedly lie elsewhere (see, e.g., Birdsong, 2018; Hyltenstam & Abrahamsson, 2000; MacWhinney, 2006; Singleton, 2001), in the so-called individual difference (ID) variables – aptitude, motivation, personality, socio-economic status, gender, learning history, and the like. That said, these variables do not supplant age effects; rather, the ID variables interact with age-related maturational constraints and exert a differential impact on learners of early and later AoAs. Hyltenstam and Abrahamsson (2000) summed it up the best when stating:

> In order to explain the individual variation among second language learners at all ages, it would be necessary to assume an interaction between maturational constraints and socio-psychological factors. In broad outline, maturational constraints would play a definite role during childhood and explain why the individual variation is quite limited between learners with early AOs [age of onsets]. Later on, in particular after the adolescent years, socio-psychological factors would take over. (p. 163)

Largely in accord with this line of reasoning, ECT-L2A mathematically arrives at an even more nuanced understanding of the changing magnitude of individual differences, as depicted in Figure 8.

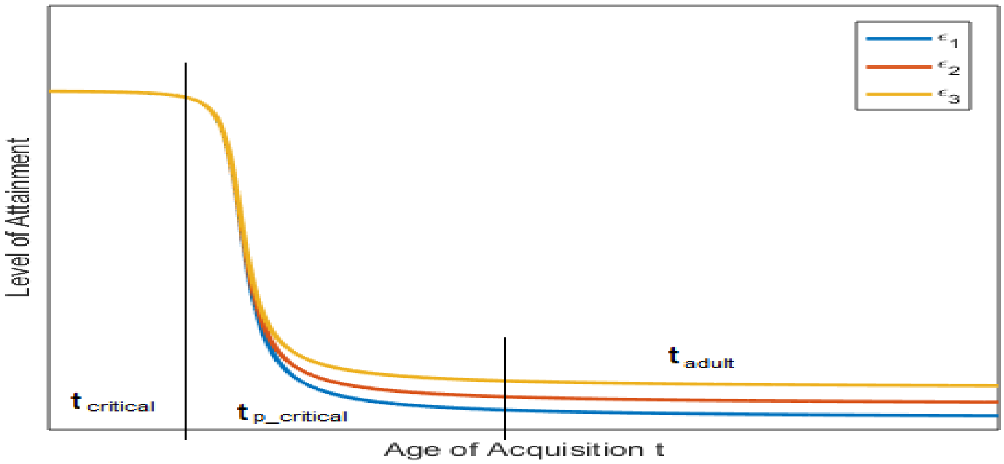

Fig. 8: Level of attainment for total energies $\varepsilon_1 < \varepsilon_2 < \varepsilon_3$

Figure 8 illustrates, based on mathematical deduction, the twin facets of interlearner differential attainment. First, attainment varies as a function of AoA. Second, attainment varies within and across the three learning periods as a function of individual learners with different amounts of total energy, $\boldsymbol{\varepsilon_1 < \varepsilon_2 < \varepsilon_3}$. Of note, individual differences play out the least among learners of AoA falling within the critical period but the most within the adult learning period (see also Abrahamsson & Hyltenstam, 2008; DeKeyser, 2000, 2012; Granena & Long, 2013; Hoyer & Lincourt,1998; Reber, 1993). During the post-critical period or what has been referred to earlier as the sensitive period, individual differences are initially non-apparent but grow more pronounced with age.

ECT-L2A thus offers a coherent explanation for variable attainment among late learners. First and foremost, it posits that individual learners' total energy or "carrying capacity" (van Geert, 1991) is different, which leads to different levels of attainment. Second, while internal (motivation and aptitude) and external (environment) energies interact over time, ultimately it is deviation energy, $\frac{\eta^2}{r^2}$, that dominates and stalls the learner at asymptote (see Equation 5).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 March 2021 doi:10.20944/preprints202103.0540.v1

ECT-L2A is in broad agreement with the bilingualism account in current CPH/L2A research, in particular, the entrenchment-transfer account proposed by MacWhinney (2006):

> The entrenchment-and-transfer account predicts a gradual decline of L2 attainment beginning as early as age five and extending through adulthood. It predicts no sharp drop, but rather a slow, gradual decline. These predictions are in good accord with the basic shape of observed AoA patterns. (p. 149)

The significance of ECT-L2A (and the entrenchment-and-transfer account, for that matter) lies in that it provides a unifying lens through which to view second language development across the human lifespan.

CONCLUSION

In this article, we specifically engaged with the debate on CPH/L2A, by *theorizing* the geometry of the age and attainment function and its underlying cause, uniquely within a singular interdisciplinary framework that brings a theoretical physics perspective and an applied linguistics perspective to bear.

ECT-L2A thus far has demonstrated a *stunning* internal consistency in that it *mathematically* identifies younger learners' superior performance to adult learners' and the differential attainment among adult learners. On the power of mathematics in scientific research, Nobel Physics Prize laureate Richard Feynman once opined:

> The rules that describe nature seem to be mathematical. This is not a result of the fact that observation is the judge, and it is not a characteristic necessity of science that it be mathematical. It just turns out that you can state mathematical laws, in physics at least, which work to make powerful predictions. Why nature is mathematical is, again, a mystery.
>
> (Feynman, 1998)

Whether mathematics and physics laws can work to make powerful predictions in a social science like applied linguistics is little known. Our experience working on ECT-L2A has given us confidence and motivation to explore further.

 doi:10.20944/preprints202103.0540.v1

At the conclusion of their seminal study on CPH/L2A, Johnson and Newport (1989) underscored three sets of facts that they argued should be accounted for by any theory of L2A: a) gradual decline of performance, b) the age at which a decline in performance is detected, and c) the nature of adult performance. ECT-L2A shines a light on all three, though, as of yet, only in broad strokes. Our subsequent theoretical work will delve into three sets of questions corresponding to the three periods ECT-L2A has now identified: the child learning period, the adolescent learning period, and the adult learning period.

First, for the child learning period:

1. When does the decline of learning begin?
2. How does it relate to the status of L1?
3. What is plasticity like in this period?
4. What does plasticity entail?
5. How is it related to a developing L1 and a developing L2?

Hartshorne *et al* (2018) cited "a lack of interference from a well-learned first language" as one of the possible causes of age-attainment function in younger versus older learners. But what has not yet been established is the nature of the younger learners' L1: What does "well-learned" mean? Is it established or is it still developing? At the very least, it cannot be a unitary phenomenon, given the age span of young learners. Continued gross-characterizations such as this are increasingly unhelpful. But then, it would seem that when the understanding of CPH/L2A (or of anything else for that matter) is entirely bottom-up, founded on empirical data, such gross, probabilistic speculations are inevitable. In consequence, the understanding is likely to remain contingent and viable for revision and reinterpretation.

Second, for adolescent learning, there is a dearth of research. According to ECT-L2A, there appear to be two sub-periods for adolescent learning. Therefore, we would like to substantiate these questions:

6. What prompted the initial dramatic decline?
7. How does each of the sub-periods relate to the status of L1?
8. How does it relate to changing plasticity?
9. How does it relate to performance in grammar?

Third, for adult learning, the traditional characterization of adult performance as either nativelike or not is woefully inaccurate. Based on our extant work, we would like, in particular, to clarify the following questions:

10. How do learners with the same L1 background and the same TL differ from each other in their ultimate attainment?
11. How do learners with different L1 background but the same TL differ from each other in their ultimate attainment?
12. What is the trajectory each of the endogenous energy (i.e., motivation and aptitude) and the exogenous energy (i.e., environmental input) in the learning process?

Further work guided by these questions will substantiate ECT-L2A, resulting in a number of highly specific predictions that can, in turn, be used to guide systematic empirical research.

REFERENCES

Abutalebi, J., & Clahsen, H. (2018). Critical periods for language acquisition: New insights with particular reference to bilingualism research. *Bilingualism: Language & Cognition, 21*(5), 883-885.

Abrahamsson, N. (2012). Age of onset and nativelike L2 ultimate attainment of morphosyntactic and phonetic intuition. *Studies in Second Language Acquisition, 34*(2), 187-214.

Abrahamsson, N., & Hyltenstam, K. (2008). The robustness of aptitude effects in near-native second language acquisition. *Studies in Second Language Acquisition*, *30*, 481-509.

Abrahamsson, N., & Hyltenstam, K. (2009). Age of onset and nativelikeness in a second language: Listener perception versus linguistic scrutiny. *Language Learning*, *59*(2), 249-306.

Bao, G, Hadrava, P, & Ostgaard, E. (1994a). Multiple images and light curves of an emitting source on a relativistic eccentric orbit around a black hole. *The Astrophysics Journal*, *425*, 63-71.

Bao, G, Hadrava, P, & Ostgaard, E. (1994b). Emission line profiles from a relativistic accretion disk and the role of its multi-images. *The Astrophysics Journal*, *435*, 55-65.

Bao, G, Wiita, P, Hadrava, P. (1996). Energy-dependent polarization variability as a signature of black holes. *Physics Review Letter*, *77*, 12-15.

Bialystok, E. (1997). The structure of age: In search of barriers to second language acquisition. *Second Language Research*, *13*, 116-137.

Bialystok, E., & Hakuta, K. (1999). Confounded age: Linguistic and cognitive factors in age differences for second language acquisition. In D. Birdsong (Ed.), *Second language acquisition and the Critical Period Hypothesis* (pp. 161-182). Mahwah, NJ: Lawrence Erlbaum.

Bialystok, E. & Miller, B. (1999). The problem of age in second language acquisition: Influences from language, structure, and task. *Bilingualism: Language and Cognition*, 2, 127-145.

Bialystok, E., & Kroll, J. (2018). Can the critical period be saved? A bilingual perspective. *Bilingualism: Language and Cognition*, *21*(5), 908-910.

Birdsong, D. (1992). Ultimate attainment in second language acquisition. *Language*, 68(*4*), 706-755.

Birdsong, D. (Ed.) (1999). *Second language acquisition and the Critical Period Hypothesis*. Mahwah, NJ: Lawrence Erlbaum.

Birdsong, D. (2005a). Nativelikeness and non-nativelikeness in L2A research. *International Review of Applied Linguistics*, 43(*4*), 319-328.

Birdsong, D. (2005b). Interpreting age effects in second language acquisition. In J. Kroll & A. De Groot (eds.) *Handbook of bilingualism: Psycholinguistic approaches* (pp. 109-127). New York: Oxford University Press.

Birdsong, D. (2006). Age and second language acquisition and processing: A selective overview. *Language Learning*, *56*, 9-49.

Birdsong, D. (2009). Age and the end state of second language acquisition. In Ritchie, W. & Bhatia, T. (Eds.), *The new handbook of second language acquisition* (pp. 401-424). Amsterdam: Elsevier.

Birdsong, D. (2018). Plasticity, variability, and age in second language acquisition and bilingualism. *Front. Psychol.* 9(*81*), 1-17.

Birdsong, D. & Molis, M. (2001). On the evidence for maturational constraints in second language acquisition. *Journal of Memory and Language*, *44*, 235-249.

Bley-Vroman, R. (2009). The evolving context of the fundamental difference hypothesis. *Studies in Second Language Acquisition*, *31*, 175-198.

Bornstein, M.H. (1989). Sensitive periods in development: Structural characteristics and causal interpretations. *Psychological Bulletin*, *105*, 179-197.

Chomsky, N. (2012). *The science of language: Interviews with James McGilvray*. Cambridge: Cambridge University Press.

Comte, A. (1959). System of positive philosophy. In R. Bierstedt (Ed.), *The making of society*. New York: Random House.

Cook, V. (1992). Evidence for multi-competence. *Language Learning*, *42*, 557-591.

Coppieters, R. (1987). Competence differences between native and non-native speakers. *Language*, *63*, 544-573.

DeKeyser, R. (2000). The robustness of critical period effects in second language acquisition *Studies in Second Language Acquisition*, *22*(4), 499-533.

DeKeyser, R. (2012). Age effects in second language learning. In S. Gass & A. Mackey (Eds.), *The Routledge handbook of second language acquisition* (pp. 422-460). New York: Routledge.

DeKeyser, R., Alfi-Shabtay, I., & Ravid, D. (2010). Cross-linguistic evidence for the nature of age-effects in second language acquisition. *Applied Psycholinguistics*, *31*(3), 413-438.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 March 2021 doi:10.20944/preprints202103.0540.v1

DeKeyser, RM., Larson-Hall, J. (2005). What does the critical period really mean? In J. Kroll & AMB, de Groot (eds). *Handbook of bilingualism: Psycholinguistic approaches*. Oxford: Oxford University Press. p.88-108.

Donaldson, B. (2011). Left-dislocation in near-native French. *Studies in Second Language Acquisition, 33*, 399-432.

Donaldson, B. (2012). Syntax and discourse in near-native French: Clefts and focus. *Language Learning, 62*(3), 902-930.

Dörnyei, Z. (1998). Motivation in second and foreign language learning. *Language Teaching*, *31*(3), 117-135.

Dörnyei, Z. & Skehan, P. (2003). Individual differences in second language learning. In C. Doughty & Long, M. (Eds.), *The handbook of second language acquisition* (pp. 589-630). Oxford: Blackwell.

Dörnyei, Z. & Ushioda, E. (2009). *Motivation, language identity, and the L2 self*. Clevedon: Multilingual Matters.

Elman, J. (2003). Development: It's about time. *Developmental Science*, *6*, 430-433.

Feynman, R. (1998). *The meaning of it all: Thoughts of a citizen scientist*. New York: Basic Books.

Foster-Cohen, S. (1993). Directions of influence in first and second language acquisition research *Second Language Research*, *9*, 140-152.

Foster-Cohen, S. (1999). SLA and first language acquisition. In W. Grabe (Ed.), *Annual Review of Applied Linguistics* (Vol. 19, pp. 3-21). Cambridge: Cambridge University Press.

Foster-Cohen, S. (2001). First language acquisition...second language acquisition: What's Hecuba to him or he to Hecuba? *Second Language Research*, *17*, 329-344.

Franceschina, F. (2005). *Fossilized second language grammars: The acquisition of grammatical gender* (Vol. 38). Amsterdam: John Benjamins.

Gardner, R. (1985). *Social psychology and second language learning: The role of attitude and motivation.* London: Edward Arnold.

Gardner, R. (2000). Correlation, causation, motivation, and second language acquisition. *Canadian Psychology*, *41*, 10-24.

Granena, G., & Long, M. (Eds.). (2013). *Sensitive periods, language aptitude, and ultimate L2 attainment.* Amsterdam: John Benjamins.

Grosjean, F. (1989). Studying bilinguals: Methodological and conceptual issues. *Bilingualism: Language and Cognition*, 1, 131-149.

Hakuta, K., Bialystok, E., & Wiley, E. (2013). Critical evidence: A test of the critical-period hypothesis for second-language acquisition. *Psychological Science, 14*(1), 31-38.

Han, Z-H. (2006). Fossilization: Can grammaticality judgment be a reliable source of evidence? In Z-H. Han & T. Odlin (Eds.), *Studies of fossilization in second language acquisition* (pp. 56-82). Clevedon: Multilingual Matters.

Han, Z.-H. (2010). Grammatical morpheme inadequacy as a function of linguistic relativity: A longitudinal study. In Z. H. Han & T. Cadierno (Eds.), *Linguistic Relativity in SLA: Thinking for Speaking* (pp. 154-182). Clevedon: Multilingual Matters.

Han, Z-H, Bao, G, & Wiita, P. (2017a). Energy conservation: A theory of L2 ultimate attainment. *International Review of Applied Linguistics in Language Teaching*, 55(*2*),133-164.

Han, Z-H, Bao, G, & Wiita, P. (2017b). Energy conservation in SLA: The simplicity of a complex adaptive system. In L. Ortega & Z-H. Han (eds). *Complexity theory and language development* (pp. 210-231). Amsterdam: John Benjamins.

Hartshorne, J. K., Tenenbaum, J. B., & Pinker, S. (2018). A critical period for second language acquisition: evidence from 2/3 million English speakers. *Cognition*, *177*, 263-277.

Herschensohn, J. (2007). *Language development and age.* New York: Cambridge University Press.

Hopp, H. (2010). Ultimate attainment in L2 inflection: Performance similarities between non-native and native speakers. *Lingua*, *120*, 901-931.

Hopp, H. (2013). Grammatical gender in adult L2 acquisition: Relations between lexical and syntactic variability. *Second Language Research*, *29*(1), 33-56.

Hoyer, W., & Lincourt, A. (1998). Ageing and the development of learning In M. Stadler & P. Frensch (Eds.), *Handbook of implicit learning* (pp. 445-470). Thousand Oaks, CA: Sage.

Hulstijn, J. H. (2015). *Language proficiency in native and non-native speakers: Theory and research.*

Hulstijn, J. H. (2019). An individual-differences framework for comparing nonnative with native speakers: Perspectives from BLC Theory. *Language Learning*, *69*, 157-183.

Hyltenstam, K., & Abrahamsson, N. (2003). Maturational constraints in SLA (pp. 539-588). In C. Doughty & M. Long (Eds.), *The handbook of second language acquisition*. New Jersey: Wiley-Blackwell

Ioup, G., Boutstagui, E., El Tigi, M., & Moselle, M. (1994). Re-examining the critical period hypothesis: A case study of successful adult SLA in a naturalistic environment. *Studies in Second Language Acquisition*, *10*, 303-337.

Jia, G. & Fuse, A. (2007). Acquisition of English grammatical morphology by native Mandarin-speaking children and adolescents: Age-related differences. *Journal of Speech, Language and Hearing Research* 50: 1280–1299.

Johnson, J.S. & Newport, E.L. (1989). Critical period effects in second language learning: The influence of maturational state on the acquisition of English as a second language. *Cognitive Psychology*, 21(*1*), 60-99.

Kellerman, E. (1995). Age before beauty: Johnson and Newport revisited. In L. Eubank, L. Selinker, & M. Sharwood Smith (Eds.), *The current state of interlanguage: studies in honor of William Rutherford (1995)* (pp. 219-231). Amsterdam: John Benjamins.

Knight, C. (2016). *Decoding Chomsky: Science and revolutionary politics*. New Haven: Yale University Press.

Lardiere, D. (2007). *Ultimate attainment in second language acquisition*. Mahwah: Lawrence Erlbaum.

Larsen-Freeman, L. (2020). Complex dynamic systems theory. In B. VanPatten, G. Keating, & S. Wulff (Eds.), *Theories in second language acquisition* (pp. 248-270). New York: Routledge.

Loehr, J., & Schwartz, T. (2005). *The power of full engagement*. Free Press.

Lenneberg, E. (1967). *Biological foundations of language*. New York: Wiley.

Long, M. (1990). Maturational constraints on language development. *Studies in Second Language Acquisition*, *12*, 251-285.

Long, M. (2005). Problems with supposed counter-evidence to the critical period hypothesis. *IRAL*, *43*, 287-317.

Long, M. H. (2007). *Problems in SLA*. Mahwah, NJ: Lawrence Erlbaum Associates.

Long, M. H. (2013). Maturational constraints on child and adult SLA. In G. Granena & M. H. Long (Eds.), *Sensitive periods, language aptitude, and ultimate L2 attainment* (pp. 3-41). Amsterdam: John Benjamins.

MacWhinney, B. (2006). Emergent fossilization. In Han, Z-H. & Odlin, T. (Eds.), *Studies of fossilization in second language acquisition*. Clevedon: Multilingual Matters.

Marinova-Todd, S., Marshall, D. B., & Snow, C. E. (2000). Three misconceptions about age and second-language learning. *TESOL Quarterly*, *34*, 9-34.

Mayberry, R. I., & Lock, E. (2003). Age constraints on first versus second language acquisition: Evidence for linguistic plasticity and epigenesis. *Brain and Language*, *87*(3), 369-384.

Meisel, J. (2009). Second language acquisition in early childhood. *Zeitschrift für Sprachwissenschaft, 28*, 5-34.

Meisel, J. (2013). Sensitive phases in successive language acquisition: The critical period hypothesis revisited. In C. Boeckx & K. Grohmann (Eds.), *The Cambridge handbook of biolinguistics*. Cambridge: Cambridge University Press.

Munoz, C., & Singleton, D. (2010). A critical review of age-related research on L2 ultimate attainment. *Language Teaching*, *44*(1), 1-35.

Newport, E.L. (1991). Contrasting conceptions of the critical period for language. In S. Carey & R. Gelman (Eds.), *The epigenesis of mind* (pp. 111-130). Hillsdale, NJ: Erlbaum.

Oyama, S. (1976). A sensitive period for the acquisition of a non-native phonological system. *Journal of Psycholinguistic Research*, *5*, 261-283.

Patkowski, M. (1980). The sensitive period for the acquisition of syntax in a second language. *Language Learning*, *30*, 449-472.

Penfield, W., & Roberts, L. (1959). *Speech and brain mechanisms*. New York: Atheneum.

Pinker, S. (1994). *The language instinct*. New York: W. Morrow.

Pulvermüller, F. & Schumann, J. (1994). Neurobiological mechanisms of language acquisition. *Language Learning*, *44*, 681-734.

Qureshi, M. (2016). A meta-analysis: Age and second language grammar acquisition. *System*, *60*, 147-160.

Reber, A. (1993). *Implicit learning and tacit knowledge: An essay on the cognitive unconscious.* Oxford: Clarendon Press.

Rogalski, M. S. & Palmer S. B. (2006). Advanced university physics (second edition), Chapman & Hall/CRC.

Saito, K. (2015). Experience effects on the development of late second language learners' oral proficiency. *Language Learning*, *65*(3), 563-595.

Schachter, J. (1996). Learning and triggering in adult L2 acquisition. In G. Brown, K. Malmkjaer, & J. Williams (Eds.), *Performance and competence in SLA* (pp. 70-88). Cambridge: Cambridge University Press.

Scovel, T. (1988). *A time to speak: A psycholinguistic inquiry into the critical period for human speech.* Cambridge: Newbury House.

Scovel, T. (2000). A critical review of the critical period research. *Annual Review of Applied Linguistic, 20*, 213-223.

Singleton, D. (2001). Age and second language acquisition. *Annual Review of Applied Linguistics, 21*, 77-89.

Sorace, A. (1993). Unaccusativity and auxiliary choice in non-native grammars of Italian and French: asymmetries and predictable indeterminacy. *Journal of French Language Studies, 3*, 71-93.

Stam, G. (2015). Changes in thinking for speaking: A longitudinal case study. In E. Bylund & P. Athanasopolous, (Guest Editors), The language and thought of motion in second language speakers. *Modern Language Journal, 99*(S1), 83-99.

van Baxtel, S. (2005). *Can the late bird catch the worm? Ultimate attainment in L2 syntax.* Utrecht: Landelijke Onderzoekschool Taalwetenschap (LOT).

van Geert, P. (1991). A dynamic systems model of cognitive and language growth. *Psychological Review, 98*, 3-53.

Wartenburger, I., Heekeren, H., Abutalebi, J., Cappa, S., Villringer, A., & Perani, D. (2003). Early setting of grammatical processing in the bilingual brain. *Neuron, 37*(1), 159-170.

Wayne, J. (2013). Physics laws of social science. *MPRA Paper*, *47811*.

White, L. & Genesee, F. (1996). How native is near-native? The issue of ultimate attainment in adult second language acquisition. *Second Language Research*, 12(*3*), 233-265.

Wichmann, S, Holman, E, & Brown, C. (2016). The ASJP database (version 17). Available at http://asjp.clld.org (4 November, 2016).

Yuan, B., & Dugarova, E. (2012). Wh-topicalization at the syntax-discourse interface in English speakers' L2 Chinese grammars. *Studies in Second Language Acquisition, 34*, 533-560.