

**JUGGLING REGULAR AND IRREGULAR VERBS: AN
EVALUATION OF RULE- AND ANALOGY-BASED MODELS AND
THE ROLE OF EXECUTIVE FUNCTIONS**

by
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ABSTRACT

JUGGLING REGULAR AND IRREGULAR VERBS: AN EVALUATION OF RULE- AND ANALOGY-BASED MODELS AND THE ROLE OF EXECUTIVE FUNCTIONS

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rule-based models, analogy-based models

Humans are remarkably good at detecting and acquiring linguistic patterns. One unavoidable challenge is not making overregularization errors (*goed). Executive Functions (EFs) – inhibitory control (IC) and working memory (WM) – have been proposed as potential mechanisms to overcome such errors, but evidence is inconsistent. This thesis evaluates a central assumption of the EF accounts: regular grammatical rules are dominant over irregular inflections. The assumption aligns with rule-based explanations, which offer separate processing for regular and irregular verbs, but contradicts analogy-based explanations that assume a shared process. Study 1 extends the analyses of an existing dataset of Dutch-speaking adults by Ferreira, Roelofs, and Piai (2020). Study 2 presents a new experiment with native Turkish-speaking adults, tested in their first (L1; Turkish) and second languages (L2; English). In Dutch and Turkish, participants were slower when switching to the regular inflection after repeating irregular inflection (irregular-irregular-regular; IIR) than when alternating (regular-irregular-regular; RIR), supporting rule-based explanations. However, IC and WM measures did not predict the IIR-RIR difference, offering no support for EF accounts. The thesis also contrasts the processing of L1 and L2, extends the exploration to non-Indo-European languages, and compares two morphologically distinct languages, Dutch and Turkish, offering a more comprehensive understanding of morphological inflection.

ÖZET

DÜZENLİ VE DÜZENSİZ FİİLLERİ BİR ARADA YÜRÜTMEK: KURAL VE ANALOJİ TEMELLİ MODELLERİN VE YÜRÜTÜCÜ İŞLEVLERİN ROLÜNÜN DEĞERLENDİRİLMESİ

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Anahtar Kelimeler: genelleştirme hataları, Yürütücü İşlevler, İngilizce geçmiş zaman, kural temelli modeller, analogi temelli modeller

İnsanlar, dilsel paternleri tespit etme ve edinmede oldukça başarılıdır. Ancak, genelleştirme hataları (*goed) yapmamak, kaçınılmaz bir zorluktur. İnhibitör kontrol (IC) ve çalışma belleği (WM) gibi Yürütücü İşlevler (EF), bu tür hataların üstesinden gelmede potansiyel bir mekanizma olarak öne sürülmüştür. Fakat, önceki bulgular tutarsızdır. Bu tez, EF yaklaşımlarının temel bir varsayımını değerlendirmektedir: düzenli gramer kuralları düzensiz çekimlere göre dominanttır. Bu varsayım, düzenli ve düzensiz fiillerin ayrı işleme yollarına sahip olduğunu öne süren kural temelli açıklamalarla örtüşmektedir, ancak, tek bir ortak işleme olduğunu öne süren analogi temelli açıklamalarla çelişmektedir. Çalışma 1, Ferreira, Roelofs, ve Piai (2020) tarafından Hollandaca konuşan yetişkinlerden oluşan mevcut bir verisetinin analizlerini genişletmektedir. Çalışma 2, anadili Türkçe olan yetişkinlerle birinci (L1; Türkçe) ve ikinci dillerinde (L2; İngilizce) test edilen yeni bir deney sunmaktadır. Hollandaca ve Türkçe’de, katılımcılar düzensiz çekimi tekrarladıktan sonra düzenli çekime geçerken (düzensiz-düzensiz-düzensiz; IIR), geçiş yaparken olduğundan (düzenli-düzensiz-düzensiz; RIR) daha yavaş olmuşlardır, ve bu, kural temelli açıklamaları desteklemiştir. Ancak, WM ve IC ölçümleri bu farkı öngörmeyerek, EF yaklaşımlarını desteklememiştir. Tez ek olarak L1 ve L2’yi karşılaştırmakta, araştırmayı Hint-Avrupa dışı dillere genişletmekte, ve morfolojik olarak farklı iki dili karşılaştırarak morfolojik çekimin daha kapsamlı anlaşılmasını sağlamaktadır.

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*To Istanbul,
for giving me every reason to grieve,
as I set sail toward a life in the UK I have yet to weave.*

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LIST OF ABBREVIATIONS

ABA	Alternating Switch
AIC	Akaike Information Criterion
BBA	Repetition then Switch
BIC	Bayesian Information Criterion
CBA	Double Switch
COCA	Corpus of Contemporary American English
EF	Executive Functions
ERP	Event-related Potentials
fMRI	Functional Magnetic Resonance Imaging
I	Irregular
IC	Inhibitory Control
L1	First Language
L2	Second Language
R	Regular
RT	Reaction Time
WM	Working Memory

1. INTRODUCTION

Language is learned in a highly complicated linguistic environment. How humans learn a language in this complexity has thus been central to cognitive science research. Learners employ cognitive and linguistic mechanisms to aid them in navigating the complexity. One such mechanism is *productivity* (Chomsky 1957; Hockett 1960). Productivity is a learning tool that allows language learners to generalize grammatical rules, freeing them from memorizing each individual linguistic unit. Therefore, human languages are unique in their creative (productive) nature (Chomsky 2006). Productivity is demonstrated when learners are introduced to nonce words created by researchers in experimental settings. In her influential work, (Berko 1958) tested children on English grammar rules by presenting them with nonce words, such as *spow* and *mot*. Children applied the relevant grammatical rule to these nonce words by, for example, uttering *spowed* or *motted* in English past tense. She famously quoted:

“It is evident that the acquisition of language is more than the storing up of rehearsed utterances, since we are all able to say what we have not practiced and what we have never before heard.” (Berko 1958, 150).

The linguistic environment, however, is not always perfect in predictability, confusing language learners. While productivity constitutes a creative aspect of human languages, inconsistencies in the input present an unavoidable challenge (O’Donnell et al. 2011). One of the key challenges is not generalizing the grammatical rules to exceptional items (i.e., irregulars). Following productivity, it is inevitable for language learners to make *overregularization errors* when the given grammatical rule is mistakenly applied to irregular items. Overregularization errors have been extensively studied in English past tense, where learners produced errors, such as **goed*, **swimmed*, **hitted*, **bringed* (Albright and Hayes 2003; Ambridge 2010; Bybee and Slobin 1982; Kidd and Lum 2008; Marchman 1997; Marchman, Wulfeck, and Weismer 1999; Marchman, Plunkett, and Goodman 1997; Marcus et al. 1992;

Maslen et al. 2004; Pinker and Ullman 2002; Rumelhart, McClelland, and AU 1986). Such errors were documented in other grammatical rules, domains, and languages, such as English transitive causatives (Ambridge and Ambridge 2020), English un-prefixation (Ambridge 2013), Turkish causatives (Nakipoğlu, Uzundağ, and Sarigül 2022), Turkish Aorist (Nakipoğlu, Uzundağ, and Ketrez 2023), as well as artificial languages (Austin et al. 2022; Hudson Kam and Newport 2005).

Language learners eventually succeed in overcoming overregularization errors throughout language development. The initial aspect to consider - to understand how the process of overcoming these errors unfolds and how irregularities are inflected correctly – would be to look into parental linguistic input children receive (Ambridge et al. 2008), specifically, whether language learners receive implicit and/or explicit feedback about which grammatical forms are correct and acceptable. Parental speech rarely involves overregularization errors (Morgan and Travis 1989), and corrective feedback was ineffective in decreasing the error rates (Marcus et al. 1992). Therefore, it is unlikely that input-related factors are one of the potential mechanisms behind overcoming overregularization errors and the correct usage of irregularities. The absence of input-related determinants makes the study of overregularization errors and correct irregular inflection an intriguing and important domain to investigate (Bowerman 1988), as understanding them opens windows into how we learn a language in the process of a quite complex linguistic environment and when productivity, a mechanism that allows language learning, does not operate consistently. Despite its importance, however, there is still no consensus on which mechanisms learners utilize to figure out how to overcome these errors and learn to balance between productive rule application and its exceptions (Seidenberg and Plaut 2014).

1.1 Executive Function (EF) Accounts

While children were shown to produce overregularization errors, adults are almost always correct in their irregular inflections (Hudson Kam and Newport 2005). Elman (1993) and Newport (1990) suggested that one potential reason is children’s underdeveloped cognitive abilities, ironically making children better learners of the specifics of their languages. When their cognitive abilities fully mature, learners become better at balancing productive rules and exceptions and stop making overregularization errors. One promising ability is *Executive Functions* (*EFs*; Hudson Kam and Chang 2009). *EFs* aid individuals in managing their everyday tasks when there

are multiple competing obstacles, making attendance to the intended and target action challenging (Diamond 2013). Indeed, irregularities serve as an obstacle that interferes with the intended inflection, possibly requiring enough EF capacities to form a balance.

EF is an umbrella term for several cognitive abilities (Diamond 2013). Among these, the current thesis focuses on inhibitory control (IC) and working memory (WM). The EF abilities were often demonstrated to help language learning and processing (Gooch et al. 2016; Miyake et al. 2000). IC – the ability to suppress and block competing unwanted information and selectively attend to the target counterpart (Williams et al. 1999) – affects language learning and processing in, for instance, language switching (Li et al. 2021), complex morphology (Gandolfi et al. 2023), (McClelland et al. 2007), and word reading (Qiu et al. 2023). WM – the ability to hold multiple types of information simultaneously in the mental space (Baddeley and Hitch 1994) – impacts language learning and processing in, for example, vocabulary learning (Gathercole 2006), sentence processing (Jefferies, Lambon Ralph, and Baddeley 2004), language comprehension (Daneman and Merikle 1996), and conceptual representation (Martin and Schnur 2019).

The overcoming of overregularization errors has been explored in relation to the contributions of both IC and WM (Hudson Kam and Chang 2009; Sahin, Pinker, and Halgren 2006), which the current thesis refers to as *IC and WM accounts* (also see Austin et al. 2022 for a similar conceptualization). Concerning the interplay between IC and overcoming overregularization errors, it was proposed that errors are a product of failing to block (inhibit) the dominant productive rule when it competes with the exceptions (Sahin, Pinker, and Halgren 2006). Concerning the interplay between WM and irregularities, when WM is still yet to mature, any information is more likely to be overestimated (Dougherty and Hunter 2003). Therefore, a limited WM capacity might engage more with the easy and salient grammatical rule than the exceptions (Hudson Kam and Chang 2009). Thus, the maturation of EF abilities can be a potential candidate for explaining how overregularization errors are avoided, and correct irregular forms are applied.

EF accounts are not necessarily mutually exclusive, as IC and WM belong to the same broader cognitive domain of EFs. They have processing intersections; for example, Diamond (2013) suggests that IC and WM contribute to each other’s processing and rarely operate entirely independently. The ability to inhibit unwanted information with IC requires the ability to maintain different information in the here and now with the help of WM (Diamond 2013). Similarly, the ability to hold multiple types of information in WM requires inhibiting irrelevant stimuli with the help of IC (Diamond 2013). Yet, in the context of overregularization errors, researchers

have mostly focused on one or the other. Thus, the current thesis instead tested the contributions of both IC and WM, referred to collectively as *EF accounts*.

1.1.1 Inhibitory Control (IC) Account

As promising as EF accounts may be, studies have revealed contrasting findings. Supporting the IC account, in Sahin, Pinker, and Halgren (2006), native English-speaking adults silently inflected regular and irregular verbs in English past tense. The fMRI results showed that the neural circuitry responsible for inhibitory processes was active while inflecting irregular verbs. Ibbotson and Kearvell-White (2015) tested English-speaking 5-year-olds on their regular and irregular past tense inflections and their relationships with IC abilities. Their findings yielded a significant prediction of IC on decreasing overall past tense errors. Similarly, Yuile and Sabbagh (2021) examined English-speaking 3- to 5-year-olds on their irregular past tense verb inflections and their relationship with IC abilities. The results revealed that children with higher IC skills produced fewer errors. However, Ferreira, Roelofs, and Piai (2020) found that adult participants did not need to inhibit the regular grammatical rule to produce correct irregular forms by showing that switching to the regular verb inflection did not result in a cost after irregular verb inflection. On a similar line, we tested Turkish-speaking children on their productions of Turkish Aorist using three different IC tasks. We found that Turkish-speaking children’s IC abilities did not predict their overregularization error rates (Nakipoğlu, Öztürk, and Kara submitted).

One explanation for the discrepancies among IC studies could be the differences between adults and children. While children continue to develop their EF skills until young adulthood, adults already have high EF abilities (Diamond 2013; Korzeniowski, Ison, and Difabio De Anglat 2021). Therefore, a significant threshold is likely to be at play, in which adults’ plateau in their EF abilities might no longer predict their correct irregular verb inflection. However, Sahin, Pinker, and Halgren (2006) found support for adults, while we in Nakipoğlu, Öztürk, and Kara (submitted) did not with children, contrasting the explanation of EFs being different in adults and children. Moreover, adults’ EF abilities can be trained and increased (Blair 2017), which shows that adults’ stable EF abilities are less likely to explain the discrepancies among studies testing the relationship between EF and irregular morphology. Thus, another explanation is needed as to why some studies supported the IC account while others failed.

1.1.2 Working Memory (WM) Account

Supporting the WM account, Hudson Kam and Chang (2009) presented participants with an artificial language in which a main determiner of the language appeared with nouns 60% of the time. In the remaining 40%, participants were exposed to inconsistent (irregular) input: either no determiner-noun combinations or combinations with other (irregular) determiners. Following the teaching phase, participants were instructed to produce the artificial language by forming sentences to describe the presented scenes. In the WM manipulation, participants were either asked to form their sentences through free sentence formation (high WM-load condition) or by arranging the flashcards in the correct order that contained the relevant words (low WM-load condition). The flashcard condition decreased participants' memory demands compared to the free sentence formation. Participants in the flashcard condition did not regularize the main (regular) determiners while they did in the free production condition. Hudson Kam and Chang (2009) suggested that adults' WM capacities are responsible for producing correct irregular forms by enabling retrieval. However, in a series of seven experiments, Perfors (2012) suggested otherwise. Using a similar artificial language, they manipulated WM load conditions during the learning phase of the language by, for example, asking participants to simultaneously rate the sensibility of unrelated sentences, the correctness of a mathematical equation, memorization of three or six unrelated letters, and so forth. Her findings revealed that the WM load did not affect the overregularization behavior of adults. The difference between Hudson Kam and Chang (2009) and Perfors (2012) was that the WM load was induced during production in the former but during learning in the latter. In a following computational analysis, Perfors (2012) found that WM limitations during learning cannot solely explain overregularization behavior. Instead, a prior learning bias for regularization must be combined with WM limitations. That is to say, unless the WM constrains the linguistic input in a particular way during the learning phase, combined with a learning bias for regularization, overregularization is unlikely to occur.

Though the explanation by Perfors (2012) is promising, it has received criticism. Goldberg and Ferreira (2022) suggest that overregularization errors do not stem from the distortion of input during learning or a bias per se but from learners' limited exposure to language. Goldberg and Ferreira (2022) argued that when the available patterns of a language are inaccessible to learners, they go with the simplest (or good-enough) option available, rather than a learning bias. Additionally, WM limitations during learning do not solely explain findings supporting the EF accounts, which were observed during production (e.g., Hudson Kam and Chang

2009; Ibbotson and Kearvell-White 2015; Sahin, Pinker, and Halgren 2006; Yuile and Sabbagh 2021). The current thesis proposed another explanation to understand the discrepancy among findings.

1.1.3 Summary of the EF Accounts

In general, the findings with regard to the interplay between EFs and overregularization errors posit a mixed and complex picture. While some studies showed a potential influence of IC and WM, others failed to do so. There could be various reasons for the observed discrepancy. First, the discrepancy might reflect the differences in EF abilities in adults and children. As adults have fully matured EFs, the predictive power of these capacities might be diminished or absent in adults. However, some adult studies have still found effects for both IC and WM accounts (e.g., Hudson Kam and Chang 2009; Sahin, Pinker, and Halgren 2006) but not child studies (e.g., Nakipoğlu, Öztürk, and Kara submitted). Second, Perfors (2012) discussed that overregularization errors might not reflect a production failure due to limited cognitive abilities, but rather a learning bias for regularization is more at play (also see Culbertson and Kirby 2016). However, the explanation by Perfors (2012) still does not account for why, during production, increasing the WM loads of adults resulted in more overregularization errors in an artificial language (Hudson Kam and Chang 2009) and why IC abilities during production were associated with irregular verb inflections of adults and children (Ibbotson and Kearvell-White 2015; Sahin, Pinker, and Halgren 2006; Yuile and Sabbagh 2021). Therefore, the current thesis introduces another perspective to describe the incompatibility among findings. One reason I suggest is the inherent assumptions underlying EF accounts about the dominance of regular grammatical rules.

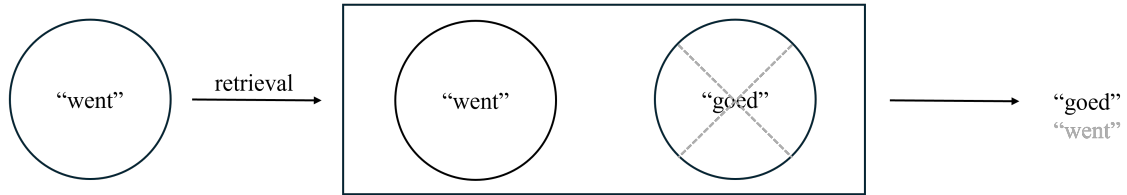
1.1.4 Assumption Underlying the EF Accounts

I propose that the already-given assumption of EF accounts is that a dominant (productive) grammatical rule (e.g., -ed past tense rule in English) is applied. The overregularized form serves as the dominant form for irregulars (*goed) that interferes with the correct irregular inflection (went). In other words, the mental space is preoccupied with the (dominant) overregularized form either by a failure during inhibition (Sahin, Pinker, and Halgren 2006) due to limited IC ability or a failure during retrieval due to limited WM capacity (Hudson Kam and Chang 2009). See Figure 1.1 for a visual representation of the IC and WM accounts, proposed by the

current thesis.

Figure 1.1 Schematic representation of IC and WM accounts' predictions

IC Account



WM Account



Note: The figure displays the summary of predictions of the IC and WM accounts on overregularization errors and correct irregular verb inflection in an example of English past tense. The IC account (up) suggests that insufficient IC capacity makes it challenging to block the predominant incorrect application of the regular grammatical rule (**goed*). Due to the blocking difficulty, speakers produce overregularization errors. The dashed lines represent an inflection scenario in which IC and WM capacities are adequate. The WM account (down) suggests that insufficient WM capacity makes it challenging to retrieve the correct irregular form (*went*) due to the predominance of the incorrect application of the regular grammatical rule (**goed*). Due to the retrieval difficulty, speakers produce overregularization errors.

The assumption, however, has caveats given the current ongoing debate about the dominance of the regular grammatical rule, namely, rule- and analogy-based explanations. Not all scholars agree with asymmetrical dominance between regular and irregular items. The presupposed assumption of rule- and analogy-based explanations in EF accounts has been mentioned briefly by other studies testing EFs (see Sahin, Pinker, and Halgren 2006). There has been neither an explicit claim nor a direct experimental examination. Sahin, Pinker, and Halgren (2006) interpreted their findings to result from either the necessity to inhibit the regular (dominant) grammatical rule (i.e., rule-based explanations) or the competing phonologically-analogous irregular forms (i.e., analogy-based explanations). However, the follow-up studies testing the EF accounts typically designed their experiments based on the assumption of the dominance of the regular grammatical rule (e.g., Ferreira, Roelofs, and Piai 2020; Hudson Kam and Chang 2009; Ibbotson and Kearvell-White 2015), while others did not make such a differentiation (e.g., Yuile and Sabbagh 2021). Yuile and Sabbagh (2021) discussed that IC can block the rule or phonologically-analogous forms, similar to Sahin, Pinker, and Halgren 2006. Nevertheless, Hudson Kam and Chang

(2009) stated that WM space is preoccupied with the salient – in other words dominant – rules. Ibbotson and Kearvell-White (2015) proposed that IC must block the overregularized form **fled* to produce the correct form *flew*. Ferreira, Roelofs, and Piai (2020) tested whether blocking the regular rule during irregular verb inflection makes the regular verb inflection more challenging.

These studies, therefore, inherently assume the presence of a differing dominance level between regular and irregular items, as supported by rule-based explanations but not by analogy-based explanations. Thus, the current thesis took the EF accounts on the basis of a given assumption about regular dominance to understand whether the assumption helps explain the discrepancy among existing studies.

Rule-based explanations posit that regular and irregular items are processed through separate pathways: regular items undergo a combinatorial process in which the dominant grammatical rule is applied, whereas irregular items are retrieved as whole-verb forms. Therefore, there is a clear dominance difference between regular and irregular items. *Analogy-based explanations*, conversely, posit that regular and irregular items are processed through a shared pathway: they depend on the system’s attempt to search for phonologically analogous forms rather than a combinatorial process. Therefore, there is no unequal dominance level between regular and irregular items.

The following section outlines a detailed overview of both rule- and analogy-based explanations. As for the scope of the current thesis, the description of these explanations was limited to their application to morphological inflections. See Ambridge (2020) and Ambridge et al. (2013) for a review of other linguistic domains.

1.2 Rule- and Analogy-based Explanations

Also referred to as dual-route models, rule-based explanations assume a clear categorical difference between their grammatical elements (Clahsen 1997, 1999; Marcus et al. 1992; Pinker 1999; Pinker and Prince 1988; Pinker and Ullman 2002; Prasada and Pinker 1993). Rule-based explanations predict regular items as subject to a combinatorial (computational) process (e.g., Past tense $\rightarrow$ verb + ed, Pinker 1999), where the regular grammatical rule is dominant (default) over the non-dominant exceptions (non-default). The combinatorial inflection for regular items operates within the grammatical system, whereas irregular items are inflected outside this system via a lexical (associative) process. That is to say, regular and irregular items are inflected via separate pathways. According to rule-based explanations, overregularization errors result from dominant rule-governed productivity. Ambridge (2010)

summarizes as follows. When the system attempts to apply a grammatical rule to an irregular verb (*throw*), it first checks the lexical memory to find the correct (*threw*) and/or phonologically similar analogous forms (*blow* → *blew*). The system blocks the regular dominant grammatical rule and produces the correct irregular form if one is successfully recalled. If retrieval fails, the combinatorial system, by default, produces the overregularized form (**threwed*).

There is some empirical evidence to support rule-based explanations. One of the most frequently utilized tasks is priming. Researchers present participants with prime and target items. If prime-target pairs are identical (and share the same processing pathway), a facilitation effect should be marked by reduced RTs during the target recognition. If, however, pairs are dissociated from each other (and share distinct processing pathways), facilitation is not observed, marked by comparable RTs during the recognition of the target. Rule-based explanations predict that, while regular prime-target pairs (*play-played*) must demonstrate a facilitation effect due to a combinatorial process and thus a shared pathway between the root and inflection, irregular pairs (*go-went*) must not (or to a markedly lesser extent) due to the absence of a combinatorial process and thus a different pathway between the root and the inflection. Several studies found a facilitation effect in regular but not irregular pairs (e.g., Clahsen et al. 2013; Silva and Clahsen 2008; Sonnenstuhl, Eisenbeiss, and Clahsen 1999).

Also referred to as single-route models, analogy-based explanations offer a single associative system for its grammatical elements (Bechtel and Abrahamsen 1990; Bybee 1988, 1995; Bybee and Hopper 2001; Rumelhart, McClelland, and AU 1986; Sokolik 1990 also see MacWhinney 2001). Analogy-based explanations predict both regular and irregular items to be inflected by probabilistic calculations via forming phonological analogies with the available items in the linguistic input – described as “on-the-fly analogy” by Ambridge 2020, 511 – rather than productive grammatical rules. Therefore, there are no unequal dominance levels between regular and irregular items, and they are inflected within the same grammatical system. According to analogy-based explanations, overregularization errors result from a higher frequency of the available regular items that are phonologically similar than the frequency of the available analogous irregular items. Ambridge (2010) summarizes as follows. If a correct inflected irregular form (*threw*) cannot successfully be recalled, the system attempts to apply correct inflection by forming mappings with analogous forms (*blow* → *blew* or *show* → *showed*). If the regular analogous item (*show* → *showed*) is higher in frequency than the irregular one (*blow* → *blew*), then the system makes overregularization errors (**threwed*).

There is also supporting evidence for analogy-based explanations. Rumelhart, Mc-

Clelland, and AU (1986) revealed that their computational model inflected untrained words by forming mappings with phonological similarities between verb roots and inflected past tense forms without the model’s explicit representation of productive grammatical rules. Ambridge (2010) implemented an acceptability judgment task for children in nonce verbs testing English past tense. The acceptability of both regular and irregular inflected forms increased as a function of the frequency of phonologically similar available forms. Blything, Ambridge, and Lieven (2018) replicated the observation by Ambridge (2010) in production. It would have supported rule-based explanations if these findings had been observed only for irregular but not regular verbs (Ambridge 2010).

The applicability of rule and analogy-based explanations is also discussed as being different in first (L1) and second languages (L2). The Declarative/Procedural model by Ullman (2004) suggested that in L1, regular items are inflected via rule application within the procedural memory, which is responsible for the gradual learning of hierarchical relationships. Irregular items are instead retrieved as whole forms within the declarative memory, which is responsible for the storage of factual information. In L2, both regular and irregular verb inflection depend on lexical memory (Ullman 2020).

In sum, the debate between rule- and analogy-based explanations remains unresolved. While some studies support the presence of the dominance of the regular grammatical rule over irregular items and hence offer separate pathways, plenty of others indicate the lack of dominance difference and hence suggest a single associative pathway. The main aim of the current thesis is to test the predictions of both rule- and analogy-based explanations to examine the influence of EFs on correct irregular verb inflection as a proposed solution to understand the inconsistent findings in studies examining the EF accounts. As explained in Figure 1.1, WM and IC accounts inherently predict that the available cognitive space must allow the correct irregular verb inflection to occur since the dominant regular rule tends to preoccupy processing space.

1.3 The Current Thesis

The current thesis tried to test the prediction that their IC and WM abilities must be involved for adults to inflect correct irregular forms without overregularizing them. The EF accounts predict that sufficient EF abilities allow a correct irregular inflection because otherwise, the predominant rule application occupies the space.

Accordingly, the thesis examined whether, in the first place, the grammatical rules are dominant over irregulars by examining rule- and analogy-based explanations alongside EF accounts. To the best of my knowledge, the current thesis is the first study to test individual differences in EFs in adults by simultaneously accounting for the underlying assumptions of rule- and analogy-based explanations.

The current thesis additionally contributed in two additional aspects: second language (L2) processing, as well as cross-linguistic generalizability of two typologically diverse languages in their morphological structures and the distributions of irregular grammar.

1.3.1 Second Language (L2) Processing

The current thesis provided an understanding of L2 processing. A comprehensive investigation of language, by definition, includes an examination of both L1 and L2. In his Declarative/Procedural model (discussed in more detail in Study 2), Ullman (2004) suggests that in L1, there is rule-based processing; in L2, there is analogy-based processing (Ullman 2020). A direct comparison between L1 and L2 on their reliance on rule- and analogy-based mechanisms allowed me to draw a more comprehensive picture of the regular and irregular verb inflection.

1.3.2 Cross-linguistic Generalizability

Firstly, the interplay between EFs and irregular verb inflection was mostly conducted with Indo-European languages (e.g., Ferreira, Roelofs, and Piai 2020; Ibbotson and Kearvell-White 2015; Sahin, Pinker, and Halgren 2006; Yuile and Sabbagh 2021). Oftentimes, typologically distinct languages yield different inferences for well-known cognitive phenomena (e.g., Gopnik and Choi 1990; Majid et al. 2004; Öztürk and Kanero 2024). Given the over-reliance on English in language research (Blasi et al. 2022), it is crucial to include typologically diverse languages to ensure linguistic research’s generalizability. There are typological differences between languages regarding the distribution of grammatical rules that have irregularities. For example, while English has many irregularities, Turkish is an overwhelmingly regular language (Aksu-Koç and Slobin 2017). The critical morphological difference must be accounted for to observe if the aforementioned predictions of EF accounts are subject to language’s typological distribution of regularities and irregularities for speakers. Thus, the current thesis recruited native Turkish adult speakers. The EF accounts

were tested by us in Nakipoğlu, Öztürk, and Kara (submitted) in Turkish-speaking children. The current thesis is the first study to examine Turkish-speaking adults.

Secondly, the processing behind regular and irregular verb inflection was mostly conducted with fusional and Indo-European languages (Nemeth et al. 2015; Study 2 provided a more detailed explanation). Fusional languages such as English and Dutch have suffixes that serve multiple functions (e.g., the *-s* suffix in *s/he sit-s* means both third-person and present simple tense). Agglutinative languages have suffixes that have unique functions and meanings (e.g., the *-r* suffix in *o açıkla-r* [*s/he explain-s*] means present simple tense only). By offering insights from re-analyzing native Dutch adult speakers and novelly testing native Turkish adult speakers, the current thesis revealed a cross-linguistic pattern in regular and irregular verb inflection. Thus, the current thesis is novel in the sense that it presents a direct comparison between a fusional (Dutch) and an agglutinative language (Turkish).

1.3.3 Summary

The current thesis proposes that a rule-based mechanism should be involved for EFs to be involved during irregular verb inflection, according to the assumption of EF accounts. Accordingly, it tested the predictions by rule- and analogy-based explanations, as well as the predictions of EF accounts. The current thesis additionally compared L1 and L2, extended findings to Turkish adults, and provided a comparison with Dutch adults.

Complementary findings are presented from a re-analysis of an already existing dataset by Ferreira, Roelofs, and Piai (2020) in Study 1 and a novel experiment in Study 2. Study 1 revisited the publicly available dataset by Ferreira, Roelofs, and Piai (2020), who examined the processing behind regular and irregular verb inflection in adult native speakers in the Dutch past tense. The re-analysis addressed the preferred task's limitations and found that regular and irregular verbs are inflected via separate pathways, with regular grammatical rules being dominant, supporting rule-based explanations in L1 (Dutch). In Study 2, the thesis conducted a novel experiment testing rule- and analogy-based explanations and further examined the EF accounts. It additionally compared L1 (Turkish) and L2 (English). Similar to Study 1, in L1, the results supported rule-based explanations. However, contrary to what was proposed, EF accounts were not supported despite the presence of a rule-based processing. L1 and L2 were different in the dominance of regular grammatical rules. In L2, regular and irregular verbs were of equal dominance. Findings held regardless of the tested languages' morphological differences.

2. STUDY 1

2.1 Introduction

Study 1 examined rule- and analogy-based explanations in L1 Dutch adult speakers. The key difference between rule- and analogy-based explanations is their assumptions about the separate inflection pathways for regular and irregular items and, hence, the dominance of the regular grammatical rule. Task dominance has been extensively tested in various cognitive phenomena – both non-linguistic (e.g., Jost, Hennecke, and Koch 2017; Wu et al. 2015) and linguistic (e.g., Gade et al. 2021; Koch et al. 2024). Very few studies have investigated task dominance in regular and irregular verb inflection. Ferreira, Roelofs, and Piai (2020) examined L1 adult Dutch speakers in Dutch past tense containing irregularities. The authors used an asymmetrical switch cost task, which assumes that switching between two tasks requires the inhibition of the previously activated task if it is dominant (Allport, Styles, and Hsieh 1994; Meuter and Allport 1999). In other words, if one of the tasks is more dominant, switching to the dominant task after completing the non-dominant will result in a higher switching cost due to the need for inhibition¹ of the dominant-interfering task than vice versa (see for a review, Declerck and Koch 2023; Kiesel et al. 2010).

2.1.1 The Experiment of Ferreira, Roelofs, and Piai (2020)

In Ferreira, Roelofs, and Piai (2020), participants inflected the past tense of the bare verb roots visually presented to them. The verb roots appeared in such an order that contained dyadic regular repeat (RR) and switch (IR) as well as irregular

1. The terms “inhibition” and “IC” were used interchangeably in the current thesis following the practices of previous studies (e.g., Munakata et al. 2011; Schall, Palmeri, and Logan 2017; Wessel and Anderson 2024).

repeat (II) and switch (RI) sequences, forming a continuous sequence flow (e.g., RRIIR...). Based on the assumptions of the asymmetrical switch cost task, if the regular inflection rule is dominant, then participants should be slower in inflecting the Nth trials of regular verbs in the IR sequences than irregular verbs in the RI sequences due to the necessity of inhibiting the regular trials if they are dominant. The RTs of the Nth trials in the RI and IR sequences were comparable in all three experiments, suggesting an absence of an asymmetrical dominance of the regular inflection rule over irregular inflection and the consequent need for an inhibitory process (Allport, Styles, and Hsieh 1994; Meuter and Allport 1999). Therefore, their findings contrasted with both the IC account and rule-based explanations.

However, the robustness of the asymmetrical switch costs task has been questioned (Gade et al. 2021, 2014), warranting further examination to interpret the task dominance and inhibition effects. In other words, whether Ferreira, Roelofs, and Piai (2020)’s experiment indicates a lack of dominance of the regular grammatical rule, as proposed by rule-based explanations, or an absence of inhibition, as proposed by the IC account, is unclear. First, whereas the asymmetrical switch costs task assumes that the switch to the dominant task results in longer RTs than a switch to the non-dominant, Yeung and Monsell (2003) reported an opposite pattern, where the RT is greater when switching from the dominant to the non-dominant task, suggesting that the task may reflect an increased top-down attentional control of the non-dominant task rather than the inhibition of the dominant task (see also Wu et al. 2015). Second, the asymmetrical switch costs task focuses only on dyads of the current trial (i.e., the Nth trial) and the immediately preceding trial (i.e., the N-1st trial), such as IR and RI sequences in Ferreira, Roelofs, and Piai (2020)’s data. However, within a continuous sequence of trials – as in Ferreira, Roelofs, and Piai (2020) – other preceding trials (e.g., N-2nd trials) can also influence RTs, complicating the interpretation of the task dominance of the regular grammatical rule. Indeed, the N-2 Repetition Costs task (outlined below) clearly documents the influence of the N-2nd trials on the Nth trials. Overall, a further examination of Ferreira, Roelofs, and Piai (2020)’s data is needed to resolve whether their findings reflect a lack of task dominance of the regular grammatical rule or a lack of inhibition.

N-2 Repetition Costs task tests two switching conditions: alternating and double switch (Mayr and Keele 2000). The alternating switch condition consists of repetition in the N-2nd and Nth trials, switching in the N-1st trials (e.g., ABA), and the double switch condition keeps switching (e.g., CBA). The assumption is that, in the alternating switch condition, the activated process in the N-2nd trial needs to be inhibited during the N-1st trial and reactivated to perform the Nth trial. Therefore, longer RTs in the Nth trials must be observed in the alternating switch condition

(ABA) than in the double switch condition (CBA). The existing evidence behind the N-2 Repetition Costs task exhibits the significance of the N-2nd trials, further raising questions about the applicability of the asymmetrical switch costs task in its interpretation of Nth trials in a continuous experimental design, as in Ferreira, Roelofs, and Piai (2020).

2.1.2 The Present Study

Given the controversies surrounding the asymmetrical switch costs task and the importance of considering the preceding N-2nd trials, Study 1 applied exploratory analyses to Ferreira, Roelofs, and Piai (2020)’s data. In other words, it tested whether Ferreira, Roelofs, and Piai (2020)’s lack of findings demonstrates a lack of task dominance between regular and irregular verb inflection – i.e., lack of support for rule-based explanations – or inhibition – i.e., lack of support for the IC account. My approach to address this was highlighting the potential impact of earlier trials (i.e., N-2nd trials) on the Nth trials as an adaptation of the N-2 Repetition Costs task. I re-analyzed every possible sequence by considering the N-2nd trials and compared the Nth trials of these sequences.

2.2 Methods

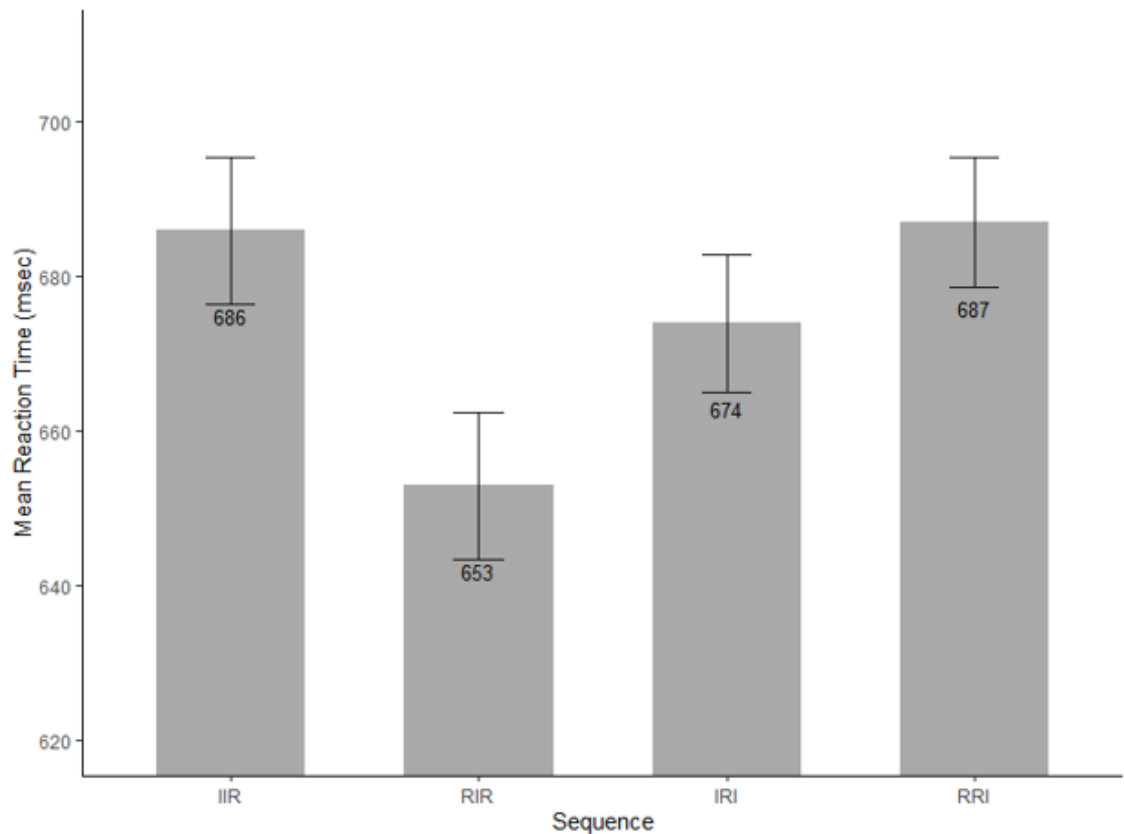
I used the publicly available data by Ferreira, Roelofs, and Piai (2020) (i.e., Ferreira and Piai 2022, <https://osf.io/szp8b/>) and re-coded each trial corresponding to regular-irregular-regular (RIR), regular-regular-irregular (RRI), irregular-regular-irregular (IRI), and irregular-irregular-regular (IIR) sequences. These four sequences of interest could only be obtained from Experiment 3 as for the first two experiments, the authors used a fixed order of RR, RI, IR, and II sequences. Thus, the entire experiment followed the RRII pattern, in which I could only have extracted RRI and IIR sequences. Sequences of regular-irregular-irregular (RII) and irregular-regular-regular (IRR) were not included, as the Nth trials of these sequences corresponded precisely to the RR and II sequences Ferreira, Roelofs, and Piai (2020) already used in their original analyses. Including them thus would not yield an additional insight beyond the original task structure of asymmetrical switch costs and would not constitute a novel re-coding. Overall, 1901 sequences were compared: 523 IIR, 427 RIR, 440 IRI, and 511 RRI.

2.3 Results

The re-coded data and the analyses are publicly available at <https://osf.io/5ruab/>. The statistical analyses were conducted using *R* 4.2.2 (Team 2024b) with *RStudio* 2024.12.0.467 (Team 2024a). T-tests were constructed using the *car* package (Fox and Weisberg 2019). For the main analyses, I constructed a linear mixed-effects regression model using the *lme4* package (Bates et al. 2015) utilizing the *bobyqa* optimizer (Powell 2009), and the *p* values were calculated using *lmerTest* (Kuznetsova, Brockhoff, and Christensen 2017). I used the *MASS* package (Venables and Ripley 2002) to identify the contrasts between sequences that were IIR-RIR, RIR-IRI, and IRI-RRI. The model included Participant and Trial (i.e., verbs) as random intercepts and Sequence Contrasts as fixed effects. The outcome variable was the RTs of the Nth trials of sequences in milliseconds. The plots were drafted using *ggplot2* (Wickham 2016).

Overall, regular ($M = 671.17$, $SD = 109.05$) and irregular verbs ($M = 680.76$, $SD = 94.13$) were inflected with equal difficulty ($t(19) = -1.04$, $p = .310$). The results from the mixed-effects model revealed that only the IIR and RIR contrast had a significant difference ($B = -37.99$, $SE = 11.28$, $t = -3.37$, $p < .001$). The IIR sequence had a higher RT cost ($M = 685.93$, $SD = 216.36$) than the RIR sequence ($M = 652.84$, $SD = 196.98$). There was a trend between RIR and IRI ($M = 673.99$, $SD = 185.67$) sequences ($B = 25.85$, $SE = 12.94$, $t = 2.00$, $p = .047$), and no difference was found between IRI and RRI sequences ($M = 686.70$, $SD = 190.22$; $B = 8.67$, $SE = 11.26$, $t = .77$, $p = .441$). See Figure 2.1 for the differences between all sequences.

Figure 2.1 RTs in the re-analysis of Ferreira, Roelofs, and Piai 2020



Note: The error bars represent Standard Errors.

2.4 Discussion

Study 1 re-coded the trials of Ferreira, Roelofs, and Piai (2020), one of the few studies investigating task dominance effects in regular and irregular verb inflection. The re-coding included trials they used in their experiment with a critique of not accounting for the inclusion of preceding N-2nd trials, in order to examine whether their null findings demonstrate the absence of task dominance in regular and irregular verb inflection, contrasting with rule-based explanations, or an absence of the necessity of inhibition of the regular grammatical rule, contrasting with the IC account.

Ferreira, Roelofs, and Piai (2020) used an asymmetrical switch cost task, which expects a higher cost when switching from a non-dominant to a dominant task than vice versa. Allport, Styles, and Hsieh (1994) argued that the increased cost was due to the necessity of inhibiting the dominant task during the engagement with the non-dominant one, which made it more costly to switch back due to inhibition.

Several studies have questioned the interpretation of inhibition (and relatedly, task dominance). For example, Yeung and Monsell (2003) reported reverse switch costs. They suggested that the cost is due to the increased top-down control to activate the non-dominant trial rather than inhibiting the dominant trial. Thus, the explanation by Yeung and Monsell (2003) contradicts the assumption about inhibition of the asymmetrical switch costs task. The explanation of Yeung and Monsell (2003) also contradicts the task’s assumption about dominance effects, as they reported reverse switch costs as opposed to Allport, Styles, and Hsieh (1994), complicating the interpretation of the asymmetrical switch costs task in accounting for task dominance and the following inhibitory effects.

Along with these explanations, another potential concern lies in the influence of preceding trials in a continuous experimental flow, as in Ferreira, Roelofs, and Piai (2020). The flow implementation likely contaminates the target Nth trials as the effect of other preceding trials cannot be excluded to isolate the true dominance and inhibition effect. N-2 repetition costs task clearly demonstrates the importance of N-2nd trials, in which if the Nth and N-2nd trials are identical, the cost is expected to be higher (Mayr and Keele 2000). Therefore, given the controversies surrounding the assumptions of the asymmetrical switch cost task (Schneider and Anderson 2010; Yeung and Monsell 2003; see Gade et al. 2014 for an overview), the thesis addressed the influence of N-2nd trials in Ferreira, Roelofs, and Piai (2020)’s data. With a similar logic, other preceding trials (e.g., N-3rd, N-4th) could also influence the Nth trials. However, the re-analysis only considered the N-2nd trials as previous studies show that the influence of earlier trials starts to dissipate (see Schuch and Keppler 2022).

The results of the re-analysis yielded that participants found it more challenging to inflect regular verbs after repeating irregular verb inflection (IIR) than switching between the two (RIR). At first glance, the difference between IIR and RIR sequences seems to reflect a mere carry-over effect (Brooks 2012) due to repeating the same task of irregular verb inflection in IIR sequences, in which repeating any task could result in task perseverance and hence in a similar switch cost regardless of what the task is or of whether it is dominant or not. However, this possibility is improbable, as a similar repetition effect was not observed during regular inflection between RRI and IRI sequences.

The switching difficulty in IIR sequences compared to the RIR sequences becomes even more substantial as the RIR sequences equate to the alternating switch condition of the N-2 Repetition Costs task (ABA). The RIR sequences likely have an inhibitory effect due to task repetition in the N-2nd, increasing RTs of the Nth trials (Mayr and Keele 2000). However, it was much more challenging for participants

to switch back to the regular inflection after repeating irregular inflection than a sequence already shown to yield long RTs (Mayr and Keele 2000)². Therefore, it presents promising evidence that in Dutch L1 adult speakers, the regular inflection rule is dominant over irregular inflection. In other words, successively engaging with the non-dominant irregular verb inflection made it more costly for participants to re-engage with the dominant regular grammatical rule.

Therefore, the null findings by Ferreira, Roelofs, and Piai (2020) do not reflect the lack of task dominance, indicating that it supported rule-based explanations in L1. The current re-analysis was also theoretically in line with their follow-up fMRI study, which revealed differential activation patterns for regular and irregular verb inflection, indicating separate pathways (Ferreira et al. 2023), complying with rule-based explanations. Another argument of rule-based explanations, in addition to the dominance of the regular grammatical rules, is that irregular items undergo a lexical/associative process. The pattern observed between IIR and RIR sequences, however, did not specifically account for the processing behind irregular verb inflection but rather yielded the presence of a dominance difference between regular and irregular items (and differential inflection patterns).

While the re-analysis showed alignment with rule-based explanations, concluding the IC account remained insufficient because the underlying cognitive process explaining the increased cost in the Nth trials of the IIR sequences is unknown. In the N-2 Repetition Costs literature, no study investigated the cognitive process behind repetition then switch (i.e., BBA) and specifically targeted the difference between ABA (i.e., alternating switch) and BBA sequences in trials of differing dominance levels.

Regardless of the underlying cognitive process, Study 1 revealed an important finding. Ferreira, Roelofs, and Piai (2020)’s data did not indicate a lack of task dominance of the regular grammatical rule, which supported rule-based explanations in L1 Dutch speakers.

2. On a similar line, higher RTs could be expected in the IRI sequences compared to the RRI sequences due to the former equating to the ABA condition of the N-2 Repetition Costs task. However, the sequences were comparable, which rightly raises questions. It is highly probable that the inhibitory process in the IRI sequences and the task repetition effects in the RRI sequences both constituted a difficulty and boosted the RTs, resulting in the absence of a significant difference.

3. STUDY 2

3.1 Introduction

Study 2 was designed specifically to examine the three-verb sequence (N-2nd, N-1st, and Nth trials) of IIR and RIR, testing rule- and analogy-based explanations, as well as to test the EF accounts, which assume the presence of the dominance of the regular grammatical rule provided by the rule-based explanations (see Figure 1.1). Study 2 additionally compared L1 Turkish and L2 English adult speakers in a within-subjects design, allowing a direct comparison between L1 and L2 as well as contributing to a cross-linguistic pattern across typologically diverse languages (Turkish and Dutch in Study 1).

3.1.1 EF Accounts Revisited

The IC account hypothesizes that overregularization errors are a consequence of a blocking difficulty of the (dominant) regular grammatical rule (see Sahin, Pinker, and Halgren 2006). Similarly, the WM account predicts that overregularization errors result from a retrieval difficulty caused by the preoccupation of WM space with the (dominant) regular grammatical rule (see Hudson Kam and Chang 2009). Consequently, children overregularize until a certain age; they overcome these errors and become adult-like as their EF abilities mature (Hudson Kam and Chang 2009).

Study 2 investigated the switch costs between the Nth trials of IIR and RIR sequences, testing the assumptions of rule- and analogy-based explanations, and examined whether individual differences in IC and WM predicted the RT difference, testing EF accounts. The investigation provided insight into the contrasting findings regarding the link between overregularization errors and EFs. For example, while English-speaking children with higher IC abilities revealed decreased error rates (Ibbotson and Kearvell-White 2015; Yuile and Sabbagh 2021), Dutch-speaking adults

and Turkish-speaking children did not utilize IC during irregular verb inflection (Ferreira, Roelofs, and Piai 2020; Nakipoğlu, Öztürk, and Kara submitted). Similarly, while adults were shown to overregularize the artificial language under high WM load (Hudson Kam and Chang 2009), it was not replicated in the following studies (Perfors 2012).

The thesis offered the inherent assumption that the dominance of the regular grammatical rules in EF accounts is a potential reason behind the discrepancy among studies. Not all scholars agree that regular and irregular items are inflected through separate pathways, where the regular grammatical rule is dominant over the other (i.e., rule- and analogy-based explanations). As rule- and analogy-based explanations have not yet converged, simultaneously testing their predictions and examining EFs will reveal an important insight into why there are mixed results in the association between EFs and overregularization errors (and correct irregular verb inflection). Study 2 provided such insight by testing participants on IIR and RIR sequences. Consequently, Study 2 is among the first to test rule- and analogy-based explanations of verb inflection accounting for the EF accounts.

3.1.2 L2 Verb Inflection

One contribution of the current thesis is the direct comparison between L1 and L2 on whether they differ in the applicability of rule- and analogy-based explanations and the role of EFs. To gain a comprehensive understanding of how language is processed in the human mind, research should not be limited to L1. It is reasonable to expect different processing patterns for L1 and L2 due to several factors, such as age of acquisition (Perani 1998), proficiency (McLaughlin 1990), and input type (Ellis and Collins 2009; i.e., native speaker input, Flege and Liu 2001). Further, some scholars suggest that L1 and L2 are deemed to differ in the dominance of regular grammatical rules and that there are separate processing pathways for regular and irregular items (Ullman 2004).

In his Declarative/Procedural model, Ullman (2004) discusses that, though they have intersections, lexicon (i.e., word-specific information) and grammar (i.e., rules) are dissociable, a distinction that maps into the dissociation of declarative and procedural memories. Declarative memory is the storage of factual and explicit representation of information (Eichenbaum 1999), while procedural memory is the storage of habitual and implicit representation of information (Cohen, Poldrack, and Eichenbaum 1997). In declarative memory, learning involves a fast mapping of idiosyncratic and arbitrary linguistic items such as bound morphemes (e.g., the),

idioms (e.g., break the ice), and more relevant to the current discussion – irregular items (Ullman 2004). In procedural memory, learning involves a slow mapping of hierarchical (computational) relationships between linguistic items such as morphological derivation (e.g., pluralization with -s), syntactic “merge” (Chomsky 2001), and more relevant to the current discussion – rule application (inflection) to regular items (Ullman 2004). In other words, while the regular items undergo a combinatorial process within the procedural memory, irregular items are retrieved as whole verb forms within the declarative memory. The regular-irregular distinction largely reflects the arguments of rule-based explanations (Prasada and Pinker 1993; Ullman 2004), and the Declarative/Procedural model further maps the regular-irregular distinction onto separate memory systems, as well as offers a processing difference in inflection between L1 and L2.

According to the Declarative/Procedural model, L1 and L2 processing of regular and irregular items should differ (Ullman 2020). First, the formation of procedural memory is much slower than that of declarative memory, putting any L2 learner/speaker at a disadvantage in learning to slowly apply the regular grammatical rule via procedural memory. Second, the ability to form procedural memory shows a decline through maturation, while the learning of declarative memory illustrates an opposite pattern, making L2 learners/speakers rely more on declarative memory even for regular items (an argument somewhat similar to the reasoning behind critical period hypothesis to L2 acquisition, see Birdsong, 1999). Third, L2 is commonly learned through formal education and explicit instruction (Elston, Tiba, and Condy 2022; Talley and Hui-Ling 2014; Williams and Colomb 1993), which is much more prone to be processed by declarative memory. Given these three reasons, the Declarative/Procedural model predicts that, while regular and irregular items will be processed via separate mechanisms in L1 (analogous to rule-based explanations), they will be processed via a single mechanism in L2 (analogous to analogy-based explanations; Ullman 2004).

Study 2 compared L1 and L2 on the assumptions of analogy- and rule-based explanations. Study 2 recruited bilinguals late rather than early, which aligns with the first two reasons. Though not many studies compared early and late bilinguals on the Declarative/Procedural model, the first two outlined reasons by Ullman (2020), by definition, include learners who learn L2 later than when the memory reliance shifts. The participants of the current thesis were L1 Turkish speakers whose L2 was English. With regard to the third reason of Ullman (2020), the English instruction in Türkiye – most like other countries – is explicit (see Akcin 2019). Additionally, English teaching contexts commonly utilize the use of the native language (Hall and Cook 2012), which is highly likely to increase L2 learners’ reliance on declarative

memory since the natural input that would help procedural automatic learning is lacking. Therefore, participant selection in Study 2 complied with all three reasons Ullman (2020) listed about why L1 and L2 should differ in the inflection of regular and irregular items, making it possible to directly test the Declarative/Procedural model on rule- and analogy-based explanations in L1 and L2.

3.1.3 Cross-Linguistic Generalizability

Another contribution of the current thesis is cross-linguistic generalizability. There are more than 4000 languages worldwide (Comrie 1988). While the same sentence is uttered by using several word units in one language (e.g., *I am crying* in English), it is uttered by only inflection in another (e.g., *Yischa* in Navajo; Baker 2001). Thus, typological differences exist, which warrants testing the same phenomenon in diverse languages to “find a way of doing justice to both the similarities and the differences without contradiction” Baker 2001, 8.

Relatedly, the over-reliance on English for cognitive sciences has recently raised significant concerns about the replicability of linguistic research (Blasi et al. 2022), and indeed, exceptions to productive grammatical rules are no ‘exception’ to the concern, having primarily been tested with English past tense (Ambridge 2010). Lately, regular and irregular processing has started to be investigated in different languages, such as Spanish, German, Dutch, Hebrew, and Russian (Berent, Pinker, and Shmiron 2002; Clahsen et al. 2010; Clahsen, Avelado, and Roca 2002; Ferreira, Roelofs, and Piai 2020; Ferreira et al. 2023; Slioussar et al. 2024). These languages, however, are mostly fusional. Via a single inflection, fusional languages can contain multiple meanings (e.g., *took* means both *take* and past tense of *take*, Pirkola 2001). In contrast, in agglutinative languages, such as Turkish, Hungarian, Swahili, and Finnish, each inflection could be separated from each other with clear-cut meaning boundaries (e.g., *yaptı* means *took* with *-tı* denoting the past tense suffix attached to the verb root *yap-* in Turkish). Productivity and irregularities have been tested with agglutinative languages as well, such as Finnish, Turkish, and Hungarian (Nakipoğlu, Uzundağ, and Ketrez 2023; Nakipoğlu, Uzundağ, and Sarigül 2022; Nemeth et al. 2015; Räsänen, Ambridge, and Pine 2016), but to a much lesser extent than fusional languages. How those differences in morphology contribute to language learning and processing still remains debated. While a line of research argues that linguistic agglutination eases language learning as opposed to fusional languages because of the transparency of suffix roles in agglutinative languages (as inflections are separated in a one-to-one correspondence between suffixation and meaning), this has not been

accepted by other researchers (Wagner, Smith, and Culbertson 2019). While the current thesis did not specifically hypothesize that typological differences between fusional and agglutinative languages would yield different and/or similar results, it suggests that the inclusion of both will contribute to cross-linguistic generalizability of regular and irregular verb inflection (Nemeth et al. 2015). A novel direct comparison between Turkish L1 speakers in Study 2 and Dutch L1 speakers in Study 1 allowed for generalizing findings to agglutinative non-Indo-European languages.

The inclusion of Turkish had one additional advantage. Studies on the association between EFs and regular and irregular verb inflection were primarily conducted in English (and Dutch, Ferreira, Roelofs, and Piai 2020) – both fusional and Indo-European languages with a rich set of irregularities. On the other hand, Turkish is a regular-rule-governed language. Regular governance is hypothesized to ease Turkish speakers’ language learning due to a highly complex and confusing morphological structure (see Nakipoğlu, Uzundağ, and Ketrez 2023). A clear typological difference in Turkish regarding its scarce distribution of irregularities would help to draw a more generalizable picture of the role of EFs on regular and irregular verb inflection. Study 2 is the first study to test the EF accounts on Turkish-speaking adults.

The present study tested Turkish-speaking adults’ production of Turkish Aorist – a tense used to express simple present tense actions and factual information, among a few grammatical rules in Turkish with irregularities. The rule operates in morpho-syntax, where one of the three Aorist suffixes is attached to the verb root: *-Ir*¹, *-Ar*, and *-r*. The *-Ir* suffix is used if the verb root includes more than one syllable (i.e., multisyllabic). The *-r* suffix is used if the verb root ends with a vowel, regardless of the syllable count. These two linguistic contexts are exceptionless, meaning the suffixation is always the same (regular) if the verb root meets the listed criteria (see Table 3.1).

The *-Ar* suffix, however, is with exceptions (irregularities). It is used if the verb root includes one syllable (i.e., monosyllabic). However, 13 verbs do not follow this rule, instead taking the *-Ir* suffix. Thus, these 13 verbs are irregular². Table 3.2 lists examples of both regular and irregular *-Ar* suffixation.

1. The letters *I* and *A* in capitals denote vowel harmony. In Turkish, there are high and low vowels. High vowels include /ɨ/, /i/, /u/, /ü/ and low vowels include /a/, /e/. According to the vowel harmony rule, the sound of the relevant suffix must be compatible with the ending vowel of the verb root. Therefore, the Aorist suffix *-Ir* is used as *-ır*, *-ir*, *-ur*, *-ür*, and *-Ar* is used as *-ar*, *-er*, depending on the verb root.

2. All of 13 irregular verbs end with sonorant consonants. However, this does not establish a regularity, as some of the *-Ar*-taking regular verbs also end with sonorant consonants. Relatedly, Turkish-speaking children overregularized the *-Ir*-taking irregular verbs by attaching the *-Ar* suffix (Nakipoğlu, Uzundağ, and Ketrez 2023).

Table 3.1 Turkish Aorist suffixation examples with *-Ir* and *-r*

	suffix	sentence
unut- (to forget)	<i>-Ir</i>	O onu unutur. (S/he forgets it)
getir- (to bring)	<i>-Ir</i>	O onu getirir. (S/he brings it)
anlat- (to tell)	<i>-Ir</i>	O onu anlatır. (S/he tells it)
ye- (to eat)	<i>-r</i>	O onu yer. (S/he eats it)
açıkla- (to explain)	<i>-r</i>	O onu açıklar. (S/he explains it)
öde- (to pay)	<i>-r</i>	O onu öder. (S/he pays it)

Notes: The table lists suffixation in Turkish Aorist with three multisyllabic verbs with consonant ending, which take the *-Ir* suffix, and three verbs with vowel ending, which take the *-r* suffix. The verbs were knowingly chosen as transitive for convenience. The underlined verbs in the sentence column denote the suffixation.

Table 3.2 Turkish Aorist suffixation examples with *-Ar* and *-Ir*

	suffix	sentence
yap- (to do)	<i>-Ar</i>	O onu yapar. (S/he does it)
at- (to throw)	<i>-Ar</i>	O onu atar. (S/he throws it)
sat- (to sell)	<i>-Ar</i>	O onu satar. (S/he sells it)
al- (to take)	<i>-Ir</i>	O onu alır. (S/he takes it)
ver- (to give)	<i>-Ir</i>	O onu verir. (S/he gives it)
bul- (to find)	<i>-Ir</i>	O onu bulur. (S/he finds it)

Notes: The table lists suffixation in Turkish Aorist with six monosyllabic verbs with consonant ending, which take the *-Ir* and *-Ar* suffix. The *-Ir* taking verbs are irregular. The verbs were knowingly chosen as transitive for convenience. The underlined verbs in the sentence column denote the suffixation.

3.1.4 The Present Study

Study 2 tested L1 Turkish adult speakers whose L2 is English on the assumptions of rule- and analogy-based explanations, trying to understand the EF accounts better. Participants completed an adaptation of the N-2 Repetition Costs task by inflecting bare verb roots in Turkish Aorist and English Past Tense with sequences of IIR and

RIR. As also outlined in the Study 1 section, it is essential to consider the N-2nd trials to test task dominance effects. While asymmetrical switch cost is generally utilized to test task dominance (e.g., Ferreira, Roelofs, and Piai 2020), in a continuous experimental flow, the presence of the N-2nd trials contaminates the Nth trials. The N-2 Repetition Costs task displays its importance. The N-2 Repetition Costs task received noteworthy support, and its predictions were replicated in various cognitive domains (Babcock and Vallesi 2015; Jost, Hennecke, and Koch 2017; Scheil and Kleinsorge 2014; Schuch and Keppler 2022) with relatively little controversy among studies (Declerck and Koch 2023, but see Kowalczyk and Grange 2017). However, a direct application and implementation of the N-2 Repetition Costs task to Study 2 was not possible.

The first reason is the lack of a third task to implement the double switch condition (i.e., task C in CBA) in the investigation of regular and irregular items. The second reason is the lack of consideration of task dominance in the N-2 Repetition Costs task. A robust experimental task that examines task dominance effects is needed since it was proposed that a successful examination of EF accounts needs to account for contrasting predictions about the dominance of the regular grammatical rule of rule- and analogy-based explanations. However, the N-2 Repetition Costs task does not initially account for dominance differences between tasks. Therefore, the current thesis adapted the N-2 Repetition Costs task by comparing RIR and IIR (i.e., ABA and BBA) sequences instead of the original ABA and CBA comparison by inserting a task repetition into the N-2nd trials of the traditional CBA sequences. The adaptation allowed for a test of rule- and analogy-based explanations to further test the EF accounts. Given the lack of research in such a domain, the underlying cognitive process behind ABA and BBA sequences (or RIR and IIR) is unclear. Consequently, EF accounts were examined by separately testing the contributions of individual differences in adults' IC and WM abilities. Individual differences in IC and WM abilities were measured to see whether they predict their performance differences in the sequences of IIR and RIR.

The final design allowed us to observe (1) rule- and analogy-based explanations, (2) EF accounts, (3) a comparison between L1 and L2, testing Ullman (2004)'s Declarative/Procedural model, (4) cross-linguistic generalizability in L1 in Turkish and Dutch (from Study 1), and (5) extension of EF accounts to an agglutinative non-Indo-European language.

3.2 Methods

3.2.1 Participants

A total of 49 native Turkish speakers with English as their L2 participated in the study. All participants were students at a university located in a suburb of a large city in Türkiye and received course credit for their participation. The English proficiency levels of participants were very high since the language of instruction in the university was English, and all students were required to reach a certain level of English proficiency to enroll. Two were excluded due to technical issues during data collection, and of the remaining 47 participants ($M_{\text{age}} = 21.97$, $SD_{\text{age}} = 4.20$, 36 females, 10 males), three were excluded from the English condition data for answering more than $\frac{1}{4}$ of trials incorrectly ($n = 1$), or technical errors during data collection ($n = 2$). All were free of vision, hearing, or motor impairments.

3.2.2 Materials

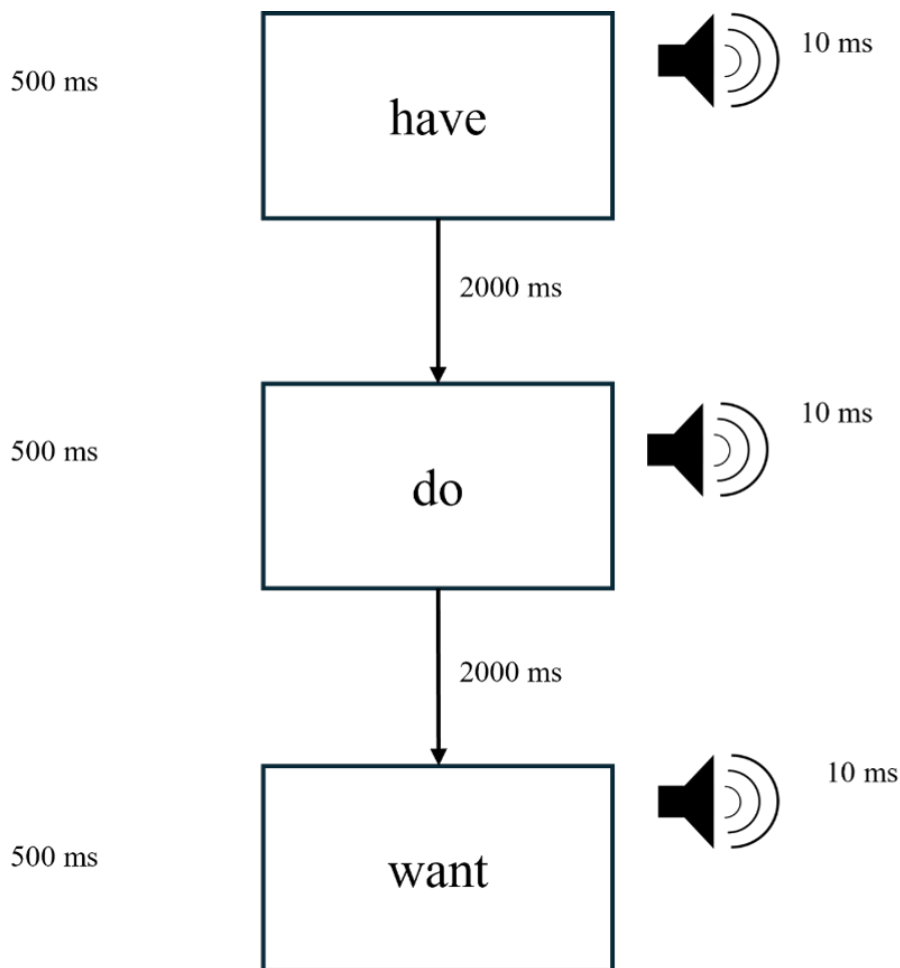
All of the materials are available at <https://osf.io/5ruab/>.

3.2.2.1 N-2 Repetition Costs adaptation: IIR-RIR sequences

The task was created and administered via *PsychoPy 2023.1.3* (Peirce et al. 2019) as an adaptation of the N-2 Repetition Costs task (Mayr and Keele 2000). In its original version, the task typically has two conditions: alternating switch (ABA) and double switch (CBA). In the ABA condition, the same task is repeatedly performed in the N-2nd and the Nth trials, and there is a switch to a different task in the N-1st trials. In the CBA condition, there are three different tasks, each of which keeps switching in N-2nd, N-1st, and Nth trials. ABA condition was adapted as RIR (regular-irregular-regular), where participants inflected regular items in N-2nd and Nth trials and irregular items in N-1st trials. A direct adaptation of the CBA condition was practically not possible due to a lack of a third task in the investigation of regular and irregular inflection. Thus, the condition was rather adapted by a modification in the N-2nd trials, in which participants repeated irregular verb inflection in the N-2nd and the N-1st trials and inflected regular verbs in the Nth trials, constituting IIR (irregular-irregular-regular) sequences. Each language condition (L1 Turkish and L2 English) involved 24 sequences (12 RIR and 12 IIR), the order of which was fully

randomized for each participant. Across these 24 sequences, a total of 72 verb roots were randomly combined, of which 24 unique verbs were repeated three times (12 regular and 12 irregular). The order of language blocks was counterbalanced across participants. Participants were instructed to inflect the verb roots on the screen and to say the Aorist form (L1 condition) or past tense (L2 condition) out loud. A 10-msec “beep” sound was presented with each verb root, and the verb remained on the screen for 500 msec. There was a 2000-msec interval between trials. See Figure 3 for an example of one sequence presented in the experiment. All sessions were audio-recorded, and the RTs were offline calculated as the time between the onsets of the beep sound and the participant’s verbal response using *Praat 6.4* (Boersma and Weenink 2023, 2001).

Figure 3.1 Sample IIR sequence from the experiment



3.2.2.2 Stimuli/verb roots

Twelve regular and 12 irregular verb roots were selected for each language condition (see Table 3.3). As discussed, English has many irregularities, while Turkish is

a regular-governed language. Turkish Aorist is among a few grammatical rules that contain morphological irregularities. There are 13 irregular Aorist verbs (see Table 3.3), one of which (i.e., “*san-*” [*to suppose*]) was excluded due to a high acceptability rate of its overregularized form (i.e., “*sanar*” [*s/he supposes*]) by native Turkish speakers (Nakipoğlu, Uzundağ, and Ketrez 2023), leaving 12 irregular verbs. Accordingly, 12 regular Aorist verbs and 12 regular and irregular English past tense verbs were selected to match the amount. The verbs were selected based on their lemma frequencies in the relevant corpora. By-verb frequency differences (high vs. low) were previously interpreted to reflect differences in lexical access. Bowden et al. (2010) discussed that faster verb inflection indicated lexical access, which reflected the processing behind higher-frequency verbs. They found frequency effects for irregular and non-dominant regular verbs but not for dominant regular verbs in L1. In L2, frequency effects were observable in all verbs (Bowden et al. 2010), supporting the Declarative/Procedural model (Ullman 2004). However, I selected the most frequent verbs because, especially for L2, unfamiliar or less frequently used verbs could constitute variability in processing speed, confounding RTs.

Table 3.3 Verb stimuli used in IIR-RIR sequences

Turkish (L1)		English (L2)	
<i>regular</i>	<i>irregular</i>	<i>regular</i>	<i>irregular</i>
yap- (to do/make)	ol- (to be)	want	have
gir- (to enter)	ver- (to give)	ask	do
bak- (to look)	al- (to take)	start	get
düş- (to fall)	kal- (to stay)	happen	come
çek- (to pull)	bil- (to know)	look	make
at- (to throw)	gör- (to see)	turn	take
sür- (to drive)	gel- (to come)	seem	think
geç- (to pass)	bul- (to find)	try	tell
sor- (to ask)	dur- (to stop)	call	know
dön- (to return)	öl- (to die)	die	see
sun- (to present)	vur- (to hit/shoot)	use	find
in- (to go down)	var- (to arrive)	need	give

For Turkish, the most frequent 12 verbs were selected using *TS Corpus V2* (Sezer 2017; cf. Uygun and Clahsen 2021). Among available corpus, *TS Corpus V2* was advantageous given the high number of tokens (491,360,398; <https://cqpweb.tscorpus.com/cqpweb/>; Sezer and Sezer 2013). For example, *Turkish National Corpus*, another widely used corpus, has 50 million tokens (<https://www.tnc.org.tr/>; Aksan et al. 2012), making use of frequencies less advantageous for the purpose of the current thesis. *TS Corpus V2* is derived from web-based data collected originally by *BOUN corpus* (<https://tulap.cmpe.boun.edu.tr/entities/>

dataset/c9f404aa-64da-4be5-a173-99b141bde7bd; Sak, Güngör, and Saraçlar 2008), making it more accessible to use syntactic annotations that allow for direct extraction of morphological lemmas (Sezer and Sezer 2013). As there are only 12 irregular verbs in Turkish Aorist, the corpora search was only conducted for regular verbs. First, a list of all regular Aorist verbs was compiled from Nakipoğlu and Üntak (2008). Then, each verb’s Aorist-inflected form was entered manually into the corpus search tool using the syntax *Morph*=".*\|+Aor\|+.*", and the results were downloaded. As the corpus occasionally included erroneous duplication from the same source, duplicates were later cleaned and removed using *MATLAB R2024b* (The MathWorks 2024). Of the most frequent regular verbs, some verbs were excluded for the following reasons:

- i.* Verbs that undergo a consonant change during suffixation in Turkish Aorist, which could potentially create a processing difficulty – e.g., *git-* → *gider* (to go → s/he goes).
- ii.* Verbs that created a new verb root with Aorist suffixation, which inflated frequency counts for the relevant lemma – e.g., *çık-* → *çıkır* or *çikar-* (to exit → s/he exits or subtract, where the latter is another verb root).
- iii.* Verbs that would normally not be used as the Aorist form in daily speech, which inflated frequency counts for the relevant lemma – e.g., *um-* → *umar* or *umarım* (to hope → s/he hopes or I hope so).

After exclusions, the remaining most frequent regular verbs were divided into two categories: sonorant- versus non-sonorant-ending. This categorization was necessary since all irregular verbs end in sonorants, which could phonologically prime participants (see Nakipoğlu and Michon 2020). Thus, the six most frequent verbs from each group (sonorant and non-sonorant) were selected. All Turkish verbs – by default – were monosyllabic, and all inflected forms were disyllabic.

For English, the most frequent 12 regular and irregular verbs were selected using the *Corpus of Contemporary American English* (*COCA*; Davies 2008). American English was chosen due to the high recognition rate by L2 speakers (Carrie and McKenzie 2018). *COCA* also has a very high number of tokens (1,001,610,938), used widely in studies (e.g., Goldberg 2016; Kyle and Crossley 2017), making it suitable for accessing reliable frequency data. Of the most frequent regular verbs, some verbs were excluded for the following reasons:

- i.* Irregular verbs that have suppletive past tense forms, which could create a processing difference – e.g., *go* → *went*.
- ii.* Irregular verbs that have multiple correct forms, which could increase RTs

reflecting a decision process – e.g., *be* → *was/were*.

- iii. Irregular verbs whose inflected forms were phonologically identical to the over-regularized forms, which would make it impossible to exclude incorrect data – e.g., *say* → *said*/**sayed*.

All irregular verbs were monosyllabic, and their inflected forms were all disyllabic. Among regular verbs, no exclusion was necessary. Only one verb (*happen*) was disyllabic, while the rest were monosyllabic. However, it was not excluded since its inflected form (*happened*) was also disyllabic, matching the rest of the stimuli.

Participants’ verbal WM, visuospatial WM, and IC abilities were assessed using correlational measures. Multiple EF measures are available in the literature. The ones below were chosen because of their wide applicability to the adult population, given the current controversies regarding the reliability of EF measures (Rouder et al., 2023), especially when adults whose EF abilities are highly mature are being assessed.

3.2.2.3 EF measures

To measure verbal WM, a computerized version of the digit-span task was used (Jones and Macken 2015), using *Psytoolkit*’s available Digit-Span task (Stoet 2010, 2017; <https://www.psytoolkit.org/experiment-library/digitspan.html>) and with small modifications to its code. The digit-span task was extensively used and tested with the adult population (Hester, Kinsella, and Ong 2004; Towse, Hitch, and Hutton 2000; Woods et al. 2011), making it a reliable measure to assess adults’ verbal WM abilities. Participants saw a random string of digits on a computer screen, and they indicated the sequence they remembered after the sequence disappeared. Starting from two digits, a longer sequence was given as the participant repeated the sequences in the correct order. The task continued until the participant missed the sequences in two consecutive trials. The longest remembered sequence became their verbal WM scores, with the highest possible score being 9.

To measure visuospatial WM, a computerized version of the Corsi Task was used (Corsi 1972), using *Psytoolkit*’s available Corsi Task (Stoet 2010, 2017; <https://www.psytoolkit.org/experiment-library/corsi.html>) and with minor modifications to its code. The Corsi task was widely applied and assessed with the adult population (e.g., Morais et al. 2018; Schaefer et al. 2022), making it a reliable measure to examine adults’ visual WM abilities. In each trial, nine purple blocks were scattered on the screen, and some blinked yellow in a specific order. Participants were instructed

to click on the blocks in order of blinking. The task started with a sequence of two blocks and continued until participants missed two consecutive trials. The longest sequence correctly remembered became their visuospatial WM scores, with the highest possible score of 9.

To measure IC, a computerized version of the Stroop task (Dyer 1973) was used through *PsychoPy 2023.1.3* (Peirce et al. 2019). The measurement of IC has previously received criticism for not measuring the isolated effects of IC but rather assessing multiple components (Nigg 2000; Simpson and Riggs 2005). Jurado and Rosselli (2007) suggested that EF measures must be selected from the battery of available tasks that have been historically shown to reflect frontal lobe functions, and the Stroop task was included in one of their suggestions. The Stroop task used here consisted of 12 trials (6 congruent, 6 incongruent) that had all the combinations of red, blue, and green ink. All 12 trials were repeated 5 times randomly. Participants completed practice trials before the main trials. Stroop values of participants who got more than half of the practice trials wrong were not analyzed. Excluding incorrect trials (West and Alain 2000), participants' IC scores were calculated by subtracting the mean RTs (in milliseconds) of the incongruent trials from the congruent trials.

3.2.3 Procedure

All participants were tested individually in a quiet room using a desktop computer. They were first presented with a consent form and then filled out the demographic form on *Qualtrics* (Qualtrics 2023). They then completed the IIR-RIR sequences with practice trials at the beginning of each language condition. Practice trials consisted of six verb roots, which were not included in the main task. The instructions and practice trials are available in Appendix A. With the aim of not priming the participants for regularity or irregularity, the stimuli for Turkish included *-r* taking verb roots in Turkish Aorist, a suffix that does not include any irregularity (see Table 3.1). Though multisyllabic verb roots, which take the *-Ir* suffix, do not include any irregularity as well, they were not chosen as practice stimuli to prevent participants from being primed by *-Ir*-taking monosyllabic irregular verbs (see Table 3.2). For English, three regular and three irregular verbs were presented. After the IIR-RIR sequences were completed, participants completed another survey asking for the meanings and inflected forms of the Turkish and English verbs used in the IIR-RIR sequences. They completed the individual difference measures (Digit-span, Corsi, Stroop) in a randomized order.

3.3 Results

All of the data and analyses are available at <https://osf.io/5ruab/>.

3.3.1 RT Calculation and Reliability Testing

Three independent coders calculated the RTs. As mentioned, the RTs were manually calculated as the duration between the onset of the beep sound and the onset of the participant’s verbal response using *Praat 6.4* (Boersma and Weenink 2023). After manual coding, the RTs were extracted using the *get_dur* script (Daland, 2004). Twenty percent of the trials were randomly selected for each participant and independently re-coded by a second coder who had not coded that participant’s responses. The Pearson’s r between the resulting RTs yielded high inter-coder reliability ($r(1360) = .99, p < .001$).

3.3.2 Data Cleaning and Descriptives

Incorrect responses were coded into three categories: overregularized, irregularized (e.g., “**giriir*” instead of “*girer*” [*to enter*]), and other (e.g., repeating the stimuli). Overall, 97% of the responses were correct. The incorrect answers were more common in the English block (5.40%) than in the Turkish block (0.77%; $\chi^2(2) = 120.84, p < .001$). The distribution of overregularized and irregularized responses was as follows: 34.62% and 34.62% in Turkish and 34.62% and 0% in English, respectively. When an incorrect response was given, the entire target sequence (IIR or RIR) was excluded from the analyses since the trial of interest was the Nth trial, which was assumed to be influenced by the preceding N-1st and N-2nd trials. For example, if the response to the N-1st trial of an RIR sequence was incorrect, all three trials from that sequence were deleted. Although I excluded certain responses deemed incorrect, the overall results remained unaffected when I adjusted how we identified their starting points: (1) When participants hesitated to give a response (e.g., uttering “*t...told*”), the onset of the hesitation “*t-*” was considered. (2) When they corrected themselves in their second responses, the onset of the second response was considered (e.g., “*telled told*”).

Participants self-reported high English proficiency ($M = 4.85, SD = .65$; out of 6), and all participants knew the meaning of verbs, though 1.19% of English past

tense inflected forms were unfamiliar to participants. These verbs, however, were not excluded from the analyses if participants inflected them correctly during the experiment.

3.3.3 Main Data Analysis

Initial analyses testing the corpus-frequency differences between stimuli and RT differences between regular and irregular verbs were conducted using *R 4.4.2* (Team 2024b) and *RStudio 2024.12.0* (Team 2024a), utilizing the *car* package (Fox and Weisberg 2019). Although the stimuli were carefully selected to match the corpus frequencies, the limited number of irregular verbs in the Turkish Aorist made it inevitable that regular and irregular verbs differed in their frequencies. 2x2 ANOVA was conducted with log transformation due to normality assumption. The results revealed that the regular stimuli (in percentages; $M = 1.01$, $SD = .76$) was less frequent than irregular stimuli ($M = 3.91$, $SD = 6.33$; $F(1, 44) = 8.20$, $p = .006$). Similarly, Turkish (L1) stimuli (in percentages; $M = .81$, $SD = 1.42$) was less frequent than the English stimuli ($M = 4.12$, $SD = 6.11$; $F(1, 44) = 49.77$, $p < .001$). There was no interaction between the corpus frequencies of regular and irregular verbs across languages ($F(1, 44) = 2.53$, $p = .119$). Lastly, the RTs for regular verbs ($M = 632.74$, $SD = 218.76$) were shorter than irregular verbs ($M = 662.88$, $SD = 226.75$; $t(46) = -6.11$, $p < .001$).

Although the main experiment included IIR and RIR sequences, post-hoc RRI and IRI sequences were extracted, allowing for an elimination of the task-repetition effects in the IIR sequences and a direct comparison with the re-analysis in Study 1. Overall, 3771 sequences were compared: 986 IIR, 979 RIR, 894 IRI, and 912 RRI. Three linear mixed-effect models were constructed using *R 4.4.2* (Team 2024b) and *RStudio 2024.12.0* (Team 2024a), and the *lme4* and *lmerTest* packages (Bates et al. 2015), using the *bobyqa* optimizer (Powell 2009). All three models included Sequence, Language, Sequence x Language interaction, Frequency as fixed effects and Participant and Verb (i.e., Stimuli) as random intercepts. Verb frequencies were included to statistically control out the unequal frequency counts of the verbs. The outcome variable was the RTs of the Nth trial of sequences in milliseconds. To identify Sequence contrasts, the *MASS* package (Venables and Ripley 2002) was applied. Interaction effects were tested with *emmeans* (Lenth 2025). Model 2 added EF tasks (i.e., Digit-Span, Corsi, and Stroop scores) as fixed effects and, Model 3 added the two- and three-way interaction between EF tasks, Language, and Sequence. The plots were drafted using the *ggplot2* (Wickham 2016) package.

Overall, Model 1 tested the rule- and analogy-based explanations. Model 2 tested the main effects of EFs. Model 3 tested the EF accounts on irregular verb inflection. All three models were compared in terms of their fits using the *performance* package (Lüdtke et al. 2019). Overall, the AIC favored Model 3, while the BIC favored Model 2. See Table 3.4 for a detailed comparison of model fit indices across all three models.

Table 3.4 Model comparison indices

	AIC (weights)	BIC (weights)	Cond. R ²
Model 1	49824.9 (<.001)	49899.7 (<.001)	0.414
Model 2	42513.0 (<.001)	42604.2 (>.999)	0.428
Model 3	42491.8 (>.999)	42710.6 (<.001)	0.436

Notes: AIC = Akaike Information Criterion. BIC = Bayesian Information Criterion. Cond. R² = conditional R-squared. The AIC favored Model 3, while the BIC favored Model 2.

3.3.3.1 Model 1

The model was entered by the following script:

RTs ~ 1 + Sequence + Language + Sequence : Language + Frequency + (1 | Participant) + (1 | Verb)

Frequency of verbs used in the experiment did not affect overall RTs of switching between regular and irregular verbs ($B = -102.78$, $SE = 201.51$, $t = -.51$, $p = .613$). There was a main effect of Language, with longer RTs in L2 ($M = 752.76$, $SD = 241.65$) than in L1 ($M = 563.43$, $SD = 164.63$; $B = -196.80$, $SE = 16.97$, $t = -11.60$, $p < .001$). The IIR-RIR sequence contrast showed no main effect ($B = 8.30$, $SE = 11.71$, $t = .71$, $p = .479$), but more importantly, an interaction effect with Language was found ($B = -35.08$, $SE = 15.77$, $t = -2.23$, $p = .026$). Whereas L2 showed no difference (IIR; $M = 722.70$, $SD = 205.99$; RIR; $M = 734.43$, $SD = 260.03$; $B = -8.30$, $SE = 11.70$; $z = -.71$, $p = .479$), L1 exhibited longer RTs for IIR ($M = 568.63$, $SD = 174.51$) compared to RIR ($M = 540.25$, $SD = 161.93$; $B = 26.79$, $SE = 10.60$, $z = 2.54$, $p = .011$). For the RRI-IRI contrast, neither the main effect ($B = -.19$, $SE = 12.46$, $t = -.01$, $p = .999$) nor the interaction with Language ($B = -6.08$, $SE = 16.52$, $t = -.37$, $p = .713$) was significant. Further, there was a trend between the IRI and RIR sequences ($B = 50.35$, $SE = 25.97$, $t = 1.94$, $p = .059$) for both languages ($B = -14.67$, $SE = 34.42$, $t = -.37$, $p = .713$).

3.3.3.2 Model 2

The model was entered by the following script:

RTs $\sim 1 + \text{Sequence} + \text{Language} + \text{Sequence} : \text{Language} + \text{Frequency} + \text{Verbal WM} + \text{Visuospatial WM} + \text{IC} + (1 \mid \text{Participant}) + (1 \mid \text{Verb})$

After the inclusion of EF measures, none of the effects observed in Model 1 changed (see Table 3.5). Among EF measures, only verbal WM ($M = 6.79$, $SD = 1.25$) predicted overall RTs. Participants with higher verbal WM abilities were quicker in switching between regular and irregular verb inflections. Their visuospatial WM ($M = 5.73$, $SD = 1.84$) and IC abilities (in milliseconds; $M = 0.04$, $SD = 0.05$) did not affect their speed in verb inflection.

Table 3.5 Fixed effect parameters of Model 2

	<i>B</i>	<i>SE</i>	<i>t</i>	<i>p</i>
Language	-190.89	17.06	-11.19	< .001***
IIR-RIR	16.68	12.47	1.34	0.181
RIR-IRI	40.41	26.28	1.54	0.130
IRI-RRI	-5.14	13.26	-0.39	0.699
IIR-RIR x Language	-44.42	16.81	-2.64	0.008**
RIR-IRI x Language	-6.90	34.83	-0.20	0.844
IRI-RRI x Language	-3.33	17.64	-0.19	0.850
Frequency	-8.24	202.94	-0.04	0.968
Digit-Span (Verbal WM)	-30.04	12.30	-2.44	0.020*
Corsi (Visuospatial WM)	4.10	9.22	0.44	0.659
Stroop (IC)	106.84	284.96	0.38	0.710

Note: ***, **, and * denote $ps < .001$, $.01$, and $.05$, respectively.

3.3.3.3 Model 3

The model was entered by the following script:

RTs $\sim 1 + \text{Sequence} + \text{Language} + \text{Sequence} : \text{Language} + \text{Frequency} + \text{Verbal WM} + \text{Visuospatial WM} + \text{IC} + \text{Verbal WM} : \text{Sequence} + \text{Verbal WM} : \text{Language} + \text{Verbal WM} : \text{Sequence} : \text{Language} + \text{Visuospatial WM} : \text{Sequence} + \text{Visuospatial WM} : \text{Language} + \text{Visuospatial WM} : \text{Sequence} : \text{Language} + \text{IC} : \text{Sequence} + \text{IC} : \text{Language} + \text{IC} : \text{Sequence} : \text{Language} + (1 \mid \text{Participant}) + (1 \mid \text{Verb})$

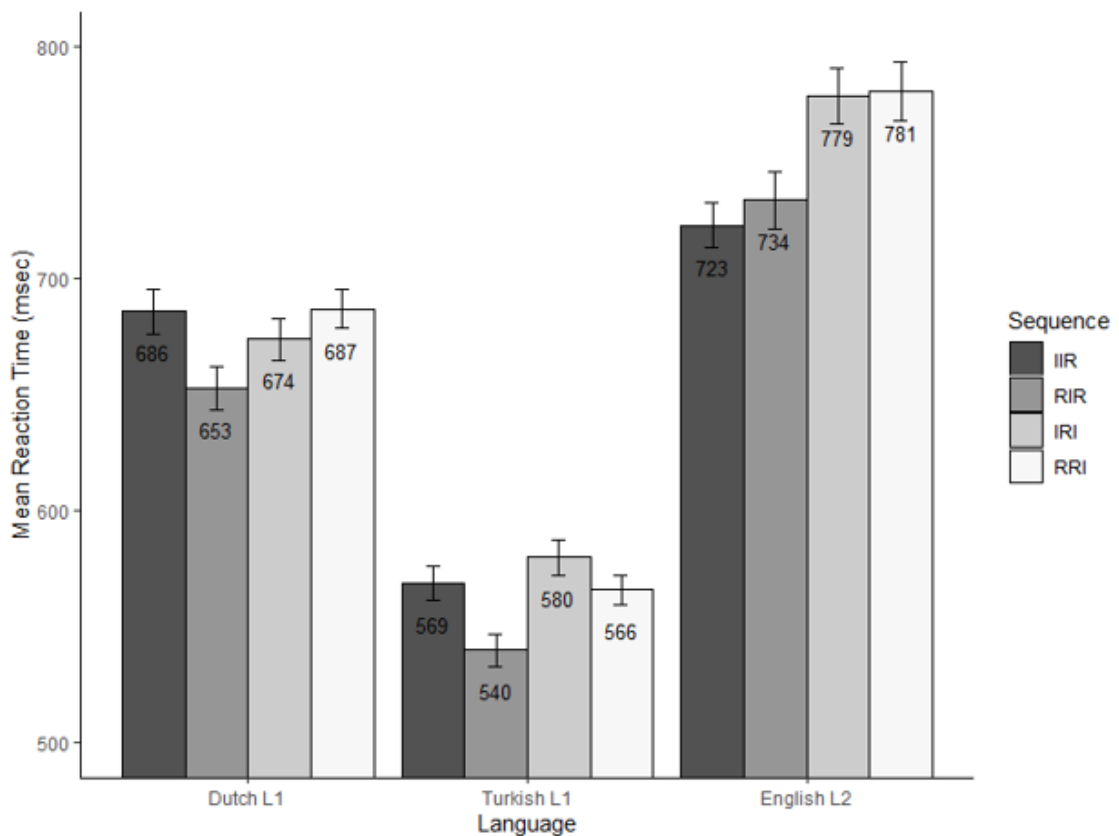
The EF accounts would predict a three-way interaction between Sequence, Language, and EF measures. However, the three-way interaction effects were non-significant. The effects observed in Models 1 and 2 did not change – except for the

main effect of verbal WM – after the inclusion of two- and three-way interactions. The number of participants in the current data ($N = 47$) is insufficient for a complex model with all tested factors and their interaction terms; regardless, Model 3 with 32 predictors is included in Appendix B.

3.3.3.4 Summary of the models

These results supported rule-based explanations in L1 and analogy-based explanations in L2, aligning with the Declarative/Procedural Model (Ullman 2004). The results also replicated the re-analysis of Ferreira, Roelofs, and Piai (2020), showing a cross-linguistic comparison between Dutch and Turkish. Figure 3.2 compares the four sequences in Dutch (L1; Ferreira, Roelofs, and Piai 2020), Turkish (L1), and English (L2). However, they did not find support for EF accounts in L1, contrary to what was proposed in rule-based explanations.

Figure 3.2 Sequence comparisons across Studies 1 and 2



Note: Error bars represent Standard Errors.

Study 2 implemented a new experiment on Turkish adult L1 speakers, whose L2 is English, testing the assumptions of rule- and analogy-based explanations alongside

EF accounts. Overall, Study 2 revealed three important findings. First, it revealed that in L1, there is a rule-based mechanism, and in L2, there is an analogy-based mechanism, supporting Ullman (2004)'s Declarative/Procedural model. Second, contrary to the proposal, it demonstrated that neither IC nor WM was involved during regular and irregular verb inflection, even though there is a rule-based mechanism. Third, it showed that findings from L1 are generalizable across languages with different morphological structures.

Research has not yet converged on the applicability of EF accounts. The current thesis proposed a potential reason: in order for IC and WM to influence regular and irregular verb inflection, they should be inflected using differential mechanisms in which the regular grammatical rule is dominant, as suggested by rule-based explanations. If there is a lexical/associative process for both regular and irregular items, then the proposals of the EF accounts would not be observable. Accordingly, the current study tested the presence of rule- and analogy-based mechanisms alongside the contributions of EFs.

The adaptation of the N-2 Repetition Costs task in Study 2 tested rule- and analogy-based explanations, and individual difference measures of EFs tested the IC and WM accounts. The results yielded that when participants repeatedly inflected irregular verbs in their L1, switching back to regular verb inflection was much more challenging, as marked by higher RTs in the Nth trials of IIR sequences compared to RIR sequences. As in Study 1, the observed IIR-RIR difference was not due to a mere carry-over effect of task repetition in IIR sequences since another sequence (RRI), which also involved task repetition, did not reveal such RT differences between IRI sequences. Consistent with the discussion outlined in Study 1, the RIR sequences were expected to yield large RTs, as they are analogous to the alternating switch condition (ABA) of the N-2 Repetition Costs task (Mayr and Keele 2000). However, IIR sequences constituted a particular challenge for participants, showing further supporting evidence for rule-based explanations in L1. The major assumption of rule-based explanations is that regular and irregular items undergo different pathways, with regular grammatical rule as dominant – a finding supported by the current results. Thus, Study 2 largely replicated Study 1, regardless of the morphological differences between a fusional language of Dutch and an agglutinative language of Turkish.

Another assumption of rule-based explanations is that irregular items undergo a lexical/associative process. However, the differences between IIR and RIR sequences cannot directly speak to the presence of a lexical/associative process but rather outline the dominance of the regular grammatical rule. Since the underlying assumption behind EF accounts and previous studies rests on the dominance difference between

regular and irregular items, the current version of the task was deemed necessary to evaluate and interpret the contributions of IC and WM.

With the replication of Study 1, Study 2 revealed that in L1, there is a rule-based processing. Turning to the main proposal of the current thesis, for EF accounts to be valid, there should be a clear dominance difference between regular and irregular items, with the regular inflection rule being dominant. Having established support for a rule-based mechanism, the next step is to discuss the applicability of EF accounts. The underlying cognitive process driving both IIR sequences and the RT difference between IIR and RIR sequences remains unknown (see Arbuthnott 2008; Jost, Hennecke, and Koch 2017; Sexton and Cooper 2017). Therefore, separately testing the EF abilities of adults was necessary. If IC and WM accounts were supported, individual differences in IC and WM abilities should have predicted the RT differences between IIR and RIR sequences. Specifically, participants with higher EF abilities should be quicker in managing the regular rule dominance, resulting in faster RT in the Nth trials of IIR sequences. However, none of the EF measures revealed an interaction effect with IIR-RIR contrasts, providing an absence of support for EF accounts. Thus, contrary to the proposal of the current thesis, though a rule-based processing was evident in L1, neither WM nor IC is associated with regular and irregular verb inflection. There are potential confounds resulting in null-effects, namely possible measure insensitivity, sample selection, and lack of multiple EF measures, which are elaborated on in the General Discussion section.

Study 2 additionally compared L1 and L2. The Declarative/Procedural model argues that in L1, regular verb inflection relies on a combinatorial process via procedural memory, whereas irregular inflection relies on lexical/declarative memory (Ullman 2004). The present findings largely supported the Declarative/Procedural model in both L1 and L2, as the Nth trials of IIR and RIR sequences were comparable in L2 but not in L1. Nevertheless, it is important to emphasize that the task used in Study 2 did not directly test for a lexical/associative process in irregular verb inflection but rather examined whether distinct processing pathways, one of which may be dominant, were involved. Thus, whether in L2, the lack of RT difference between IIR and RIR sequences reflects a single associative mechanism for regular and irregular items should be made more explicit. However, the findings still provided support for the Declarative/Procedural model as it showed separate processing pathways in L1 but not in L2.

One potential drawback could be the fact that L1 and L2 conditions also differed in language (Turkish vs. English), complicating interpretations of whether the effects reflect L1-L2 differences or cross-linguistic Turkish-English differences. Though it needs further clarification, cross-linguistic differences are unlikely to fully explain

the findings, given that studies replicated each other in Dutch and Turkish. Though L2 was not compared across languages, replication results from Study 1 strengthen the argument that the processing behind regular and irregular verb inflection is independent of the specific language's typology but rather reflects differences in L1 and L2.

Study 2 was the first study to test the EF accounts on Turkish adults, i.e., with an agglutinative language. Thus, it contributed to the universality of effects in non-Indo-European languages. It additionally provided a direct comparison between Turkish and Dutch in L1 processing of regular and irregular items, showing that languages' morphological differences in how they treat inflections did not affect the support for rule-based explanations. The cross-linguistic differences and their contributions are elaborated further in the General Discussion.

4. GENERAL DISCUSSION

Language is highly complicated, and learners face a big challenge in figuring out the complexity. Productivity, as one of the hallmarks of language, enables language learners to generalize the linguistic rules and to create novel forms (Berko 1958; Chomsky 1957; Hockett 1960). However, language is not only about rules and productivity; countless unpredictabilities in the linguistic input produce yet another complication. The difficulty arises in avoiding productive generalizations, such as using the regular past-tense *-ed* rule to form the past tense of irregular verbs in English. Learners initially make overregularization errors by incorrectly applying regular grammatical rules to irregular items, and they somehow eventually learn the correct applications (Marcus et al. 1992). To understand how humans are capable of learning and producing language despite the puzzling input they receive, it is critical to examine how language learners eventually free themselves from overregularization and produce correct irregular forms.

Different accounts have been proposed to explain how speakers come to avoid overregularization errors and produce correct irregular forms with minimal mistakes, but the precise mechanism is yet to be uncovered (Seidenberg and Plaut 2014). Some researchers argue that children’s underdeveloped cognitive capacities facilitate their learning, making the complex input more analyzable by parsing it into smaller chunks. Ironically, this immature cognitive space also leads learners to overregularize the input (Hudson Kam and Chang 2009).

4.1 EF Accounts

Executive Function (EF) abilities allow individuals to balance competing stimuli and attend to the goal-relevant input (Diamond 2013). Among EFs, the current thesis focused on Inhibitory Control (IC) and Working Memory (WM), which have been proposed as key mechanisms for managing regular grammatical rules and their

exceptions. IC allows individuals to block unwanted information and attend to the wanted information (Williams et al. 1999). When IC capacity is insufficient, learners may fail to block or inhibit the more salient (dominant) productive rule application (**goed*), leading it to override the correct irregular form (*went*; Sahin, Pinker, and Halgren 2006). WM ability allows individuals to hold different pieces of information simultaneously at present (Baddeley and Hitch 1994). When WM capacity is insufficient, learners may fail to retrieve the correct irregular form (*went*) as the available WM space is preoccupied with the more salient (dominant) productive rule application (**goed*; Hudson Kam and Chang 2009).

With regard to the association between IC and the overcoming of overregularization errors, Sahin, Pinker, and Halgren (2006) conducted an fMRI study and reported that the inhibitory neural circuitry of adult native speakers was active during irregular verb inflection in English past tense. Along the same lines, Ibbotson and Kearvell-White (2015) and Yuile and Sabbagh (2021) found that children with higher IC capacities produced fewer errors in the English past tense. However, a recent study by Ferreira, Roelofs, and Piai (2020) did not support the IC account with adults' irregular verb inflection in the Dutch past tense. A recent study we conducted also failed to find support for the IC account, showing an absence of influence of IC skills on Turkish-speaking children's overregularization errors in Turkish Aorist (Nakipoğlu, Öztürk, and Kara submitted).

With regard to the association between WM and the overcoming of overregularization errors, Hudson Kam and Chang (2009) experimentally manipulated the WM loads of adult participants. In their artificial language learning task, overregularization errors increased in the high-WM-load condition. However, Perfors (2012) found that adults performed similarly under high versus low WM loads while learning the artificial language.

Then, what could explain why some studies point to the role of EFs in overcoming overregularization errors while others do not? The first possibility is the differences in EFs between adults and children. EFs are mature and relatively stable in adults, but in children, EFs are going through rapid growth and keep developing until around young adulthood (Best and Miller 2010; Diamond 2013; Korzeniowski, Ison, and Difabio De Anglat 2021). However, the differential trajectories of adults and children are less likely to explain inconsistencies among studies testing the relationship between EF and irregular verb inflection. This is because some adult studies found that EFs are related to overregularization errors or irregular verb inflection (Hudson Kam and Chang 2009; Sahin, Pinker, and Halgren 2006), whereas some child studies reported null findings (Nakipoğlu, Öztürk, and Kara submitted). The second possibility is cognitive (EF) limitations during the learning phase

of a language rather than during production (Perfors 2012). However, limitations during the learning phase do not explain EF findings linked to overregularization errors and irregular verb inflection during production (Hudson Kam and Chang 2009; Ibbotson and Kearvell-White 2015; Sahin, Pinker, and Halgren 2006; Yuile and Sabbagh 2021). A third possibility, proposed by the current thesis, aligns with the core assumption of EF accounts: the existence of a dominant rule-based mechanism responsible for applying the regular grammatical rule.

I suggest that the central assumption underlying EF accounts is that EF abilities enable the correct inflection of irregular verbs when the regular rule application is dominant. In other words, WM and IC are theorized to aid in retrieving or selecting the correct irregular form in the face of a competing, default regular rule. While some of the studies testing the EF accounts explicitly or implicitly assumed the presence of rule dominance (e.g., Ferreira, Roelofs, and Piai 2020; Hudson Kam and Chang 2009; Ibbotson and Kearvell-White 2015), others were less clear in their conceptualizations (e.g., Sahin, Pinker, and Halgren 2006; Yuile and Sabbagh 2021). Not all scholars agree that regular and irregular verbs are processed through separate pathways, with the regular grammatical rule being dominant. Therefore, it is essential to investigate whether regular and irregular items indeed demonstrate differing dominance levels. The examination is crucial to understand the applicability of EF accounts among inconsistent findings. Rule-based explanations suggest that regular and irregular verbs are inflected via separate pathways, with regular grammatical rules being dominant (Marcus et al. 1992; Pinker 1999; Pinker and Prince 1988). On the other hand, analogy-based explanations posit that regular and irregular verbs are processed within the same pathway, where the inflections depend on phonological similarities between available regular and irregular forms, without any rule-induced dominance differences (Bybee 1988, 1995; Rumelhart, McClelland, and AU 1986). Although both perspectives received empirical support (Ambridge 2010; Blything, Ambridge, and Lieven 2018; Clahsen et al. 2013; Silva and Clahsen 2008; Sonnenstuhl, Eisenbeiss, and Clahsen 1999), no consensus has been reached.

4.1.1 Present Findings

The current thesis is among the first experimental studies to examine the assumptions of rule- and analogy-based explanations to understand the role of EFs in overcoming overregularization errors and producing correct irregular verb inflection. Study 1 re-analyzed the available dataset by Ferreira, Roelofs, and Piai (2020), which did not find support for the IC account. L1 Dutch speakers inflected Dutch past

tense forms containing irregularities in an asymmetrical switch costs task. The task assumes that if one of the trials is more dominant than the other, switching to the dominant trial should result in longer RTs than switching to the non-dominant trial due to the necessity to inhibit the previously activated dominant response (Allport, Styles, and Hsieh 1994). However, some studies found reversed costs, i.e., switching to a non-dominant trial resulting in longer RTs, and attributed the pattern to the necessity of increased attention to perform the non-dominant task (Yeung and Monsell 2003). The results of Ferreira, Roelofs, and Piai (2020) were inconclusive in terms of whether their findings indicated a lack of regular dominance (as opposed to rule-based explanations) or inhibitory processes (as opposed to the IC account). Differentiating the ambiguity, I re-analyzed their data by additionally considering their N-2nd trials because the preceding trials in a continuous experimental flow could potentially influence the RTs of the Nth trials, thereby complicating the interpretation further. For example, in the N-2 Repetition Costs task, repeating the same task in the N-2nd and Nth trials (ABA; alternating switch condition) could result in greater switch costs than a non-repetition (CBA; double switch condition) due to the need to overcome inhibition during the re-activated task in the N-2nd trials (Mayr and Keele 2000). N-2 Repetition Costs task clearly outlines the importance of preceding N-2nd trials, strengthening the need for re-analyzing the data by Ferreira, Roelofs, and Piai (2020). In my re-analysis, I extracted and compared irregular-irregular-regular (IIR), regular-irregular-regular (RIR), regular-regular-irregular (RRI), and irregular-regular-irregular (IRI) sequences.

Study 2 conducted a novel experiment with IIR and RIR sequences. The task was adapted from the N-2 Repetition Costs task with a modification of the double switch condition (CBA) due to the absence of a third trial in the investigation of regular and irregular items and the task's lack of consideration of dominance differences between trials, which was needed to test rule- and analogy-based explanations. Overall, the re-analysis in Study 1 and the experimental task design in Study 2 tested the rule- and analogy-based explanations.

The results from Studies 1 and 2 revealed that participants in both Dutch and Turkish took longer on the Nth trials of IIR sequences than on the RIR sequences in their native languages. Since no difference was observed between RRI and IRI sequences, the delay cannot be attributed to task perseverance due to mere repetition alone. Instead, the findings show that participants had difficulty switching back to the dominant regular rule after engaging with the non-dominant irregular verbs. The observed patterns support rule-based explanations on verb inflection, indicating that regular and irregular items are inflected via separate pathways and that regular grammatical rules dominate over irregular inflection. If no difference were found

between IIR and RIR sequences, it would have been interpreted as no interference from regular verb inflection on irregular verb inflection, implying equal dominance and a single associative pathway, and thus would have supported analogy-based explanations.

Before elaborating more on EF accounts, support for rule-based explanations in this thesis needs discussion. Rule-based explanations predict that irregular verbs undergo a lexical/associative process while regular verbs are inflected within a combinatorial system. The present study design did not specifically test whether irregular verbs undergo an associative process, as offered by rule-based explanations, but instead examined the presence of separate processing pathways and dominance differences. Nevertheless, the current study aligns better with rule-based explanations (Clahsen et al. 2013; Marcus et al. 1992; Pinker 1999; Pinker and Prince 1988; Silva and Clahsen 2008; Sonnenstuhl, Eisenbeiss, and Clahsen 1999) and contrasts with analogy-based explanations (Ambridge 2010; Blything, Ambridge, and Lieven 2018; Bybee 1988, 1995; Rumelhart, McClelland, and AU 1986). It should be noted that while rule- and analogy-based explanations have been considered to compete with each other, the recent literature no longer excludes the presence of the opposing end (Ambridge 2010) as Nakipoğlu, Uzundağ, and Ketrez 2023, 437 state in the discussion of the developmental course of Turkish Aorist, “a model of morphological learning that is driven by analogy at the outset and that invokes rule-induction in later stages”. Likewise, while the current study aligns with the rule-based explanations, it does not address the absence (or presence) of the analogy-based processes.

With the findings aligning with rule-based mechanisms in place, the next question becomes: *Can we now see the influence of EFs?* The test of individual difference measures of EFs in Study 2 helped to address this question. Contrary to the proposal of the thesis, neither IC nor WM explained the difference between IIR and RIR sequences, indicating the absence of EF accounts. In other words, even though regular grammatical rule served as the dominant form, the difficulty arising from its dominance is not resolved by EFs.

Before discussing the inapplicability of EF accounts and alternative explanations to understand how regular and irregular forms are inflected correctly, I list below the influence of potential confounds in the study design.

4.1.2 Potential Confounds

One potential explanation for the findings is the insensitivity of the individual difference measures used in Study 2. The concern applied especially to the IC measure

rather than the WM measure, as the WM abilities of participants predicted their overall RTs, showing at least some measurement sensitivity. Rouder, Kumar, and Haaf (2023) argued that correlational measures of IC show weak inter-measure correlations, making it difficult to interpret the null effects resulting either from an absence of effect or experimental noise. One of their suggestions is to increase the trial numbers. In the Stroop task used in Study 2, the trial number was moderately high, mitigating concerns about measurement noise.

Another possible explanation is the sample characteristics of Study 2. Participants were university students from a highly ranked institution in Türkiye who potentially have higher-than-average IC abilities (see Dvorak 2024), which would have resulted in a ceiling effect, leading to undetectable individual differences. Rouder, Kumar, and Haaf (2023) discussed that a negative value is unlikely to be observed in Stroop tasks, but a few participants exhibited negative values in my data, revealing a non-standard sample not representing a typical hypothesized “normal” population. Similarly, Stroop values generally score around the average of 0.60 (Rouder, Kumar, and Haaf 2023), but our sample showed a mean value of 0.40, yielding relatively less difficulty between incongruent and congruent trials, indicating high IC abilities. Thus, the IC skills of the current non-typical sample might obscure existing individual differences’ predictive effects, even if they exist. However, it is noteworthy that our recent study with children (Nakipoğlu, Öztürk, and Kara submitted) did not show an effect of IC skills on overregularization errors despite children’s wider range of EF abilities (Diamond 2013).

Finally, another plausible explanation for the null findings is that, in this study, the Stroop task was the only task used to assess individual differences in IC. However, IC can encompass differential sub-processes, and different tasks may tap into these IC skills to varying degrees (Nigg 2000; Rouder, Kumar, and Haaf 2023). Though the exact dissociation among IC skills remains unclear (Diamond 2013), different tasks and IC skills can affect morphological processing differently (Gandolfi et al. 2023). Notably, however, Nakipoğlu, Öztürk, and Kara (submitted) used three different IC batteries with children, and none were associated with overregularization errors.

Although the measure and sample characteristics of Study 2 may have contributed to the null findings, which were further evaluated in the Limitations and Future Directions section, the absence of EF effects begs another refinement as to why there were controversies among studies testing the IC and WM accounts on irregular processing and overregularization errors.

4.2 Learning Biases

Even though there was a rule-based processing and the regular inflection rule appeared to be dominant, the current thesis did not provide support for EF accounts. One potential explanation is that cognitive limitations during learning, as opposed to production, lead to overregularization errors (Perfors 2012). As also discussed, this explanation cannot fully account for findings supporting the role of EF during production. However, it gives a promising depiction of how EFs could be related to overregularization errors while learning the linguistic input. In her experiment and computational analysis, Perfors (2012) argued that the effect of WM is pronounced if and only if it distorts the input during learning in the presence of a prior linguistic bias for regularization. Regularization bias is considered universal and language-specific, and it is transmitted culturally throughout language evolution (Culbertson and Kirby 2016). Perfors (2012) modeled this bias alongside WM limitations in her computational analysis and found that a prior bias for regularization did not solely explain the expected overregularization behavior of the model. However, when the input was low in frequency in the model (i.e., “*tiny data*”; Perfors 2012, 497), the influence of bias became visible. Given that WM limitations additionally limited the input frequency in her model, she concluded that a prior bias for overregularization, combined with insufficient WM capacity distorting the input, leads to overregularization errors.

The explanation of Perfors (2012) fits with null findings of EF accounts with adults, including the current thesis and Ferreira, Roelofs, and Piai (2020), as the influence of WM was prevalent during the learning of the artificial language in Perfors (2012), which is not the case for adults who already mastered the language. However, Perfors (2012) still does not fully align with our recent null findings with children (Nakipoğlu, Öztürk, and Kara submitted), who are still in the learning phase with the so-called learning bias and have (relatively) low EF abilities to distort the input. One plausible reason could be that while Perfors (2012) offers a satisfactory explanation about the influence of WM on overregularization behavior, the explanation lies in *why* learners overregularize rather than addressing *how* learners ultimately stop making these errors and start to produce correct irregular forms, as proposed by EF accounts. Thus, if EF accounts fail to explain *how* irregular verbs are inflected correctly, the next question becomes: *What does help learners correct overregularization errors according to the literature?*

4.3 Statistical Learning as an Alternative Explanation

The present study did not support the EF accounts on overregularization errors, even though rule-based processing appeared to explain the inflection of regular and irregular verbs. Contrary to earlier proposals, inconsistencies across some studies testing EF accounts may lie in how they conceptualize the problem, focusing on *why* overregularization errors occur rather than *how*. I suggest that the null findings from the current thesis, Ferreira, Roelofs, and Piai (2020), as well as Nakipoğlu, Öztürk, and Kara (submitted) may indicate that, rather than relying on EF capacities, adult speakers avoid overregularization errors with the help of statistical learning mechanisms, as they mature and attuned to the linguistic input. According to the literature, one plausible explanation accounting for how learners avoid overregularization errors and become adult-like in correctly inflecting irregular verbs is statistical learning.

Already in infancy, language learners are sensitive to the distributional patterns present in their languages (Romberg and Saffran 2010). The sensitivity enables learners to track and calculate the transitional probabilities of the linguistic input, a capacity often called the statistical learning ability (Saffran, Aslin, and Newport 1996). In the phrase *happy dog*, for example, the syllables within each word (*happy*, *dog*) co-occur more predictably than the syllables across words (*py-do*), helping learners to find word boundaries (Erickson and Thiessen 2015). Although traditionally having been discussed in the context of word learning (Saffran, Aslin, and Newport 1996), statistical learning is widely used as a theoretical framework to understand other aspects of language learning (Isbilen and Christiansen 2022). It can similarly apply to the avoidance of overregularization errors suggested by the *statistical pre-emption hypothesis*.

According to the statistical pre-emption hypothesis, learners overcome overregularization errors with a probabilistic inference that, if a form or construction was correct or acceptable, I would have heard it by now (Goldberg 1995). Thus, learners overcome overregularization errors in time by tracking specifics in the input with mechanisms like statistical learning (Saffran, Aslin, and Newport 1996). In other words, the production of **goed* is statistically pre-empted due to the repeated occurrences of *went*. The more the correct form is heard, and the less the incorrect form is encountered, the more likely learners are to stop using productive generalizations. Ambridge et al. 2018, 2 summarize the statistical pre-emption in daily terms as follows.

”In all the royal greetings I’ve observed, people have addressed the Queen as Your Majesty and never as Lizzy, even though the latter would seem to convey the desired meaning (i.e., it is her name). I will now therefore tentatively assume that Your Majesty, rather than Lizzy, is the (more) permissible form of conveying this meaning (i.e., addressing the Queen).”

Overregularization is also observed in the form of other morphological errors (e.g., generalization of un-prefixation “**unclose*” instead of “*open*”; Ambridge 2013), and syntactic errors (e.g., “**I’m dancing it*” instead of “*I’m making it dance*”; Ambridge and Ambridge 2020). Various theoretical views have been proposed to explain how learners overcome overregularization errors, including the statistical pre-emption (cf. entrenchment, Braine and Brooks 1995; verb-semantics, Pinker 1991), each accounting for different types of overregularization errors at different linguistic levels, to varying degrees. Ambridge et al. (2013) review a wide range of overregularization errors and the theoretical backgrounds behind avoiding the errors. Regarding the focus of the current thesis—morphological overregularizations, and more specifically, inflectional morphology—statistical pre-emption is discussed as the most plausible explanation for how speakers avoid overregularization errors in inflectional morphology (Ambridge et al. 2013).

Once the correct forms are learned and internalized, the role of EFs can be minimal—if required at all—for speakers to produce irregular forms correctly. However, this explanation still does not explain why Ibbotson and Kearvell-White (2015) and Yuile and Sabbagh (2021) found an association between IC skills and irregular verb inflection in children, Sahin, Pinker, and Halgren (2006) in adults. Regarding the two child studies, one possible explanation is that they did not differentiate between regular and irregular verb inflection errors. Yuile and Sabbagh (2021) presented participants with only irregular verbs, and Ibbotson and Kearvell-White (2015) did not differentiate between errors in regular and irregular verbs in their analyses. EFs are undoubtedly closely linked to language (Gooch et al. 2016; Miyake et al. 2000), and the effect observed in Yuile and Sabbagh (2021) and Ibbotson and Kearvell-White (2015) might reflect the influences of EF on overall grammatical abilities, rather than specifically affecting overregularization errors. Regarding the findings by Sahin, Pinker, and Halgren (2006), I provide further discussions in the Limitations and Future Directions section.

4.4 Declarative/Procedural Model on L1 and L2 Differences

Another contribution of the current thesis is directly comparing the presence of rule- and analogy-based explanations to test the EF accounts in L1 vs. L2 processing. L2 processing differs from L1 processing (e.g., Johnson et al. 1996) due to factors like age of acquisition (Perani 1998), proficiency (McLaughlin 1990), and native speaker input (Flege and Liu 2001). Whether the difference is quantitative (e.g., L2 processing is slower) or qualitative (e.g., mechanisms behind L2 processing are different) is debated (Clahsen et al. 2010). Ullman’s Declarative/Procedural model supports the latter view and claims that the processing of regular and irregular items differs between L1 and L2 (Ullman 2020, 2004). Inherently, the model aligns with rule-based explanations in L1 and analogy-based explanations in L2, though the Declarative/Procedural model is a more general theoretical framework for dissociating memory and language systems (Ullman 2004).

According to Ullman (2004), irregular verbs are processed within declarative memory (memory for factual and explicit information), while regular verbs are processed within procedural memory (memory for habitual and rule-based information). Learning through lexical memory is much faster than procedural memory (Ullman 2004), and thus, individuals rely more on declarative memory than procedural memory for grammar in L2 than in L1. This is because individuals are typically less exposed to L2 than L1, and as a result, less time is available for L2 grammatical structures to become proceduralized through the slow learning of procedural memory (Ullman 2020). The developmental course of declarative and procedural memories differs in that learning through procedural memory begins earlier than declarative memory, and learning via one system blocks learning through the other (Ullman 2020). Thus, when L2 is learned later in life, learning shifts to declarative memory without the same degree of proceduralization as L1 (Ullman 2020). Lastly, because L2 is often taught using explicit teaching methodologies, the reliance is more likely to be on declarative memory. While speakers rely on rule-based procedural memory for regular items but declarative memory for irregular items in L1, they process and represent both in the declarative memory system in L2. The Declarative/Procedural model was supported empirically (Bowden et al. 2010; Prieto 2009; Ullman et al. 1997; but see Kidd and Kirjavainen 2011; Safaie 2021) as well as by the current thesis.

Study 2 of the current thesis supports the Declarative/Procedural model by longer RTs in IIR sequences than RIR sequences in L1 but similar RTs in L2. In other words, the Study 2 results showed that regular grammatical rules are dominant over

irregulars, and they are inflected using separate pathways in L1 (Turkish) but not in L2 (English). The characteristics of participants fit the reasons Ullman (2020) outlined as to why L1 and L2 processes should be different in their reliance on distinct memory systems for regular and irregular items. For one, the participants were late L2 learners (i.e., not bilingual by birth) and received explicit instruction about English at schools in Türkiye (see Akcin 2019). They were nevertheless highly proficient in their L2 (English) and demonstrated adequate familiarity with the verbs used in the experiment, eliminating insufficient knowledge of the language as a confounding factor. One potential criticism may lie in the fact that the L1 and L2 conditions also differed in languages. The observed support for the Declarative/Procedural model could be attributed to Turkish-English differences. While still possible, this explanation seems unlikely as, for L1, a consistent pattern in Turkish and Dutch.

Study 2, however, contrasts with a study by Safaie (2021) regarding the Declarative/Procedural model. In a speeded grammaticality judgment task, Safaie (2021) presented L1 and L2 English speakers with correct and incorrect regular and irregular forms of English past tense, i.e., overregularization and irregularization errors, in sentences. Detection of an error was taken as an indication of a combinatorial process for that verb type (regular or irregular). Both L1 and L2 speakers were more accurate in differentiating between correct and incorrect regulars (overregularization errors) but not between correct and incorrect irregulars (irregularization errors), suggesting that both L1 and L2 speakers processed regular verbs in a combinatorial fashion but accessed irregular verbs at the lexical level (Safaie 2021).

A big difference between Study 2 and Safaie (2021) is the experimental design. The single-word presentation in the present study might have created a floor effect for late L2 speakers, masking any L2 effects in the IIR-RIR sequences. Safaie (2021) argued that the presentation method of the verbs can influence the required access for rule application (if it exists). The issue is not only because presenting verbs in sentences is more naturalistic and encompasses what really is happening during rule application but also because single-word presentation can incur time pressure, especially for L2 speakers. Such time pressure may limit L2 speakers' ability to process compositional structure, even if they engage in rule-based processing (Safaie 2021). The RTs were much longer in the L2 than the L1 condition, showing a slower processing of L2. Thus, it is possible that the single-word presentation method employed by Study 2 might have created difficulty for L2 speakers in accessing the representation for combinatorial processing.

4.5 Cross-Linguistic Generalizability of the Findings

Another contribution of the current thesis was extending findings to a non-Indo-European language and directly comparing fusional and agglutinative typologies through the re-analysis conducted in Study 1. This thesis is among the first to examine Turkish-speaking adults on EF accounts and to compare typologically different languages based on the rule- and analogy-based explanations. Studies testing regular and irregular verb inflection mainly were conducted with fusional languages (Nemeth et al. 2015), and a direct comparison of fusional and agglutinative languages remains lacking; the tests of Turkish in Study 2 and Dutch in Study 1 contributed to this gap.

Languages differ in their morphological structures. For example, while some languages rely on a morphological parsing of one-to-many correspondences between suffixes and functions, i.e., fusional languages, others use a one-to-one mapping, i.e., agglutinative languages. Languages also differ in the distribution of regular and irregular items. While Turkish is a predominantly regular language, English and Dutch are not. Whether typological differences in fusion versus agglutination are related to learnability remains an open question (Wagner, Smith, and Culbertson 2019). The current thesis did not make specific predictions about how the mentioned morphological contrasts might interact with rule- and analogy-based models or EF accounts. Nonetheless, the growing concern over the overreliance on English in language research calls for broader cross-linguistic validation of psycholinguistic theories (Blasi et al. 2022).

The current results revealed that, regardless of the language morphologies, in L1, regular and irregular verb inflection relied on differential processing pathways in both Dutch- and Turkish-speaking adults, supporting rule-based explanations. Similarly, the absence of EF effects in Turkish-speaking adults indicates that, regardless of the distributional characteristics of irregularities, the explanatory power of EF accounts for how overregularization errors are avoided is limited. The use of Turkish and a comparison between Turkish and Dutch strengthened the reliability of the current results by showing a relatively language-independent pattern.

4.6 Limitations and Future Directions

Earlier sections already touched on the limitations of the current thesis, but this section provides a more detailed and comprehensive overview. First, while the contribution of EFs was unsupported here, the activation of an inhibitory circuitry during irregular verb inflection found by Sahin, Pinker, and Halgren (2006) cannot be interpreted with the explanations offered here. One issue is the sample characteristics of Study 2. The participants in this study were all university students who might have higher-than-average EF abilities, failing to represent a typical population. Sahin, Pinker, and Halgren (2006) used fMRI to detect the inhibitory processes, and thus, it is still possible that the influence of EFs could not be behaviorally captured in the present sample but is observable with neurophysiological measures (and with another, more representative sample). For example, the inhibitory processes hypothesized to block the dominant response in switch cost tasks (e.g., the asymmetrical switch cost task by Allport et al., 1994) have been examined based on event-related potentials (ERPs). In their ERP study, Wu et al. (2015) found increased negativity in the centro-frontal area during task inhibition, or the N2, which is typically seen as reflecting cognitive control (Folstein and Van Petten 2008) and response inhibition (Jodo and Kayama 1992). Measuring ERPs during the present task, future research may use the existence or absence of N2 to conclude whether an inhibitory process is involved in switching to the Nth trial after repeatedly inflecting irregular verbs in the N-2nd and N-1st trials.

Second, while the Study 2 results align with rule-based explanations, the task of comparing IIR-RIR sequences falls short in evaluating analogy-based explanations. As Sahin, Pinker, and Halgren (2006) also mentioned, the interference from linguistic items could work in two ways: interference of the dominant grammatical rule (as tested by the IIR-RIR task in the current study) or of the competing phonologically analogous forms. For example, the irregular verb *throw* and the regular verb *show* could compete during the past tense inflection of *blow*. Thus, to see if, during adulthood, both rule- and analogy-based explanations aid adults during their inflections, the same task could be designed to specifically examine the presence of analogy-based processing. Similarly, while one major claim of rule-based explanations is that regular and irregular items are processed via separate pathways, with regulars being dominant, another key claim is that irregulars undergo associative, phonology-based processing. The current study focused on the former point but did not investigate the latter. The stimulus selection could be designed to account for phonology-based interference in irregular verbs to observe if rule-based explanations

indeed provide the full explanation.

Third, in Study 2, L1 and L2 conditions also differed in the language participants were asked to inflect: Turkish and English. Even though the dominance of the regular grammatical rule was observed in both Turkish and Dutch in participants' L1, showing a cross-linguistic pattern across morphologically different languages, Turkish and English remain quite different languages. This distinction potentially could have affected the observed L1 and L2 differences. Specifically, Turkish is a verb-final language whose speakers might engage with meaning-anticipation as they process and produce a sentence. Since the presentation method used in Study 2 was single-word, this property of Turkish may have lead to processing differences relative to English. Relatedly, without a sentential context, verb inflections in Turkish can take on alternative meaning interpretations. This aspect was controlled for alternative verb-derivations via excluding such occasions (e.g., the Aorist form of *çık-* *to exit*] → *çıkır-* [*s/he exits*] can also mean [*to make someone/something exit*]). However, it was not controlled for alternative nominal forms (e.g., the Aorist form of the verb *dön-* [*to turn*] → *döner* [*s/he turns*] could also mean *a type of meat* in Turkish). Therefore, the single-word presentation could also lead to processing differences arising from meaning ambiguity in Turkish compared to English. Another relevant difference is that the overregularized forms could be deemed as correct in some regional dialects. In other words, the perceived ungrammaticality (i.e., acceptability) of overregularization errors could differ between Turkish and English. While Turkish participants still showed slower inflection times for irregular than regular verbs, reflecting a processing difference between regular and irregular verbs, cross-linguistic differences identified here must be accounted for by future research. Studies could ideally use the same language for both L1 and L2 conditions with a between-subjects design, or morphologically similar languages (e.g., Turkish and Japanese) with a within-subjects design.

5. CONCLUDING REMARKS

As one way to account for the inconsistent findings among studies on overregularization errors and EFs, this thesis evaluated the underlying assumption that regular and irregular verbs are inflected through a dominant regular grammatical rule and subordinate irregular forms. This assumption is not accepted by those who argue for verb inflections through phonological analogies. While the findings in the current thesis support rule-based processing, the involvement of EFs was not observed, which is in line with the existing literature that found a limited role of EFs. The investigation testing a non-Indo-European language and both L1 and L2 contributed to a broader and more comprehensive understanding of how humans learn to produce language properly despite challenges posed by an inconsistent and complex linguistic environment.

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APPENDIX A

Instructions and Practice Stimuli used in the Main Task (i.e., IIR-RIR Sequences) in Study 2

The instructions were given in the native language of participants (i.e., Turkish). For the purpose of the Appendix, [*the English translation*] is also provided next to each instruction. Minor differences between the Turkish and English versions largely reflect condition-specific wording, such as references to Turkish vs. English verbs, or to the Turkish present tense (Aorist) vs. the English past tense. The example verbs given in the instructions were chosen specifically not to prime participants with any regularity or irregularity, just like the practice stimuli.

Turkish (L1) Condition

Instructions:

Deneyin bu kısmında karşınıza bazı Türkçe fiiller gelecek ve bu fiilleri görür görmez sözel olarak Türkçe geniş zaman hâline dönüştürmeniz gerekecek. Örneğin, karşınıza “ilerle-” fiili çıkacak ve bu fiili gördüğünüz anda “ilerler” demeniz beklenecek. Bu örnekte olduğu gibi, gördüğünüz fiili 3. tekil şahıs ile dönüştürmeniz isteniyor. Yani “ilerlerim”, “ilerlersin”, “ilerlerler” gibi formlar değil, yalnızca “ilerler” demelisiniz. Şimdi yapmanız gerekene alışmanız için kısa bir pratik yapacağız. Devam etmek için lütfen herhangi bir tuşa basınız.

[*In this part of the experiment, you will encounter some Turkish verbs and you will need to verbally convert these verbs to the Turkish present tense as soon as you see them. For example, you will encounter the verb “ilerle-” and you will be expected to say “ilerler” as soon as you see this verb. As in this example, you are asked to convert the verb you see to the 3rd person singular. In other words, you should only say “ilerler”, not forms like “ilerlerim”, “ilerlersin”, “ilerlerler”. Now we will do a short practice to get you used to what you need to do. Please press any key to continue.*]

Lütfen fiili gördüğünüz an dönüştürünüz.

[*Please convert the verb as soon as you see it.*]

Tebrikler! Şimdi deneye başlamaya hazırsınız! Deneyde, pratikte yaptığınız gibi karşınıza bazı Türkçe fiiller gelecek ve bu fiilleri gördüğünüz an sözel olarak geniş

zaman hâline dönüştüreceksiniz. Yine pratikte olduğu gibi, geniş zaman hâline çevirirken lütfen üçüncü tekil şahsı baz alınız. Pratikten farklı olarak, bu sefer doğru cevaplar görünmeyecek ve deney bitene kadar gördüğünüz fiilleri dönüştürmeye devam edeceksiniz. Bu kısım yaklaşık 6-7 dakika sürecektir. Deneye başlamak için lütfen herhangi bir tuşa tıklayınız.

[Congratulations! Now you are ready to start the experiment! Just like in the practice, you will encounter some Turkish verbs and you will need to verbally convert these verbs to the Turkish present tense as soon as you see them. Again, as in practice, please base your answer on the third person singular. Unlike practice, this time the correct answers will not be visible and you will continue to convert the verbs you see until the experiment is over. This part will take approximately 6-7 minutes. Please press any key to continue.]

Lütfen fiili gördüğünüz an dönüştürünüz.

[Please convert the verb as soon as you see it.]

Practice Stimuli:

- i. çürü- [to rot]
- ii. acı- [to pity / to hurt]
- iii. şişmanla- [to fatten]
- iv. yargıla- [to judge]
- v. açıkla- [to explain]
- vi. kuru- [to dry]

English (L2) Condition

Instructions:

Deneyin bu kısmında karşınıza bazı İngilizce fiiller gelecek ve bu İngilizce fiilleri görür görmez sözel olarak İngilizce geçmiş zaman hâline dönüştürmeniz gerekecek. Örneğin, karşınıza “play” veya “sleep” fiili çıkacak ve bu fiili gördüğünüz anda ‘played’ veya ‘slept’ demeniz gerekecek. Şimdi yapmanız gerekene alışmanız için kısa bir pratik yapalım. Devam etmek için lütfen herhangi bir tuşa tıklayınız.

[In this part of the experiment, you will encounter some English verbs and you will need to verbally convert these verbs to the Turkish present tense as soon as you see them. For example, you will encounter the verb “play” or “sleep” and you will be expected to say “played” or “slept” as soon as you see this verb. Now let’s do a short practice to get you used to what you need to do. Please press any key to continue.]

Lütfen fiili gördüğünüz an dönüştürünüz.

[*Please convert the verb as soon as you see it.*]

Tebrikler! Şimdi deneye başlamaya hazırsınız! Deneyde, pratikte yaptığınız gibi, karşınıza bazı İngilizce fiiller gelecek ve bu İngilizce fiilleri gördüğünüz anda sözel olarak geçmiş zaman hâline dönüştüreceksiniz. Pratikten farklı olarak, bu sefer doğru cevaplar görünmeyecek ve deney bitene kadar gördüğünüz fiilleri dönüştürmeye devam edeceksiniz. Bu kısım yaklaşık 6–7 dakika sürecektir. Deneye başlamak için lütfen herhangi bir tuşa tıklayınız.

[*Congratulations! Now you are ready to start the experiment! Just like in the practice, you will encounter some English verbs and you will need to verbally convert these verbs to the English past tense as soon as you see them. Unlike practice, this time the correct answers will not be visible and you will continue to convert the verbs you see until the experiment is over. This part will take approximately 6-7 minutes. Please press any key to continue.*]

Lütfen fiili gördüğünüz an dönüştürünüz.

[*Please convert the verb as soon as you see it.*]

Practice Stimuli:

- i. close
- ii. win
- iii. speak
- iv. walk
- v. work
- vi. break

APPENDIX B

Results from Model 3 in Study 2

The following table shows Model 3 conducted as a linear mixed effects model for Study 2. The model includes Participant and Verb (i.e., Stimuli) as random intercepts. Fixed effects were Sequence, Language, Sequence x Language interaction, Frequency, Digit-Span, Corsi, Stroop, and two- and three-way interactions between executive function tasks, Language, and Sequence as fixed effects. The outcome variable was the RTs of the Nth trial of sequences in milliseconds. . The model tested the executive function accounts based on the three-way interactions. Model 3 was built on Model 2, including two- and three-way interactions of the executive function tasks, Language, and Sequence. The inclusion did not alter the results obtained from Models 1 and 2 (except for the main effect of Digit-Span), and the added interaction effects were non-significant, contrasting with the executive function accounts.

Table B.1 Fixed effect parameters of Model 3

	<i>B</i>	<i>SE</i>	<i>t</i>	<i>p</i>
Language	-193.49	16.72	-11.58	< .001***
IIR-RIR	17.64	12.50	1.41	0.158
RIR-IRI	37.74	25.84	1.46	0.150
IRI-RRI	-5.62	13.34	-0.42	0.673
IIR-RIR x Language	-45.78	16.79	-2.73	0.006**
RIR-IRI x Language	-3.87	34.21	-0.11	0.910
IRI-RRI x Language	-2.91	17.64	-0.17	0.869
Frequency	-12.96	198.74	-0.07	0.948
Digit-Span	-18.54	12.57	-1.48	0.148
Corsi	-12.76	9.57	-1.33	0.189
Stroop	70.04	290.61	0.24	0.811
Language x Corsi	25.61	4.16	6.15	< .001***
IIR-RIR x Corsi	-7.45	8.39	-0.89	0.375
RIR-IRI x Corsi	5.26	8.75	0.60	0.547
IRI-RRI x Corsi	12.86	8.94	1.44	0.150
Language x Digit-Span	-18.45	4.98	-3.70	< .001***
IIR-RIR x Digit-Span	3.07	10.22	0.30	0.764
RIR-IRI x Digit-Span	13.96	10.66	1.31	0.191
IRI-RRI x Digit-Span	-8.62	10.97	-0.79	0.432
Language x Stroop	66.57	114.90	0.58	0.562
IIR-RIR x Stroop	-500.85	233.06	-2.15	0.032*
RIR-IRI x Stroop	290.28	244.36	1.19	0.235
IRI-RRI x Stroop	-144.34	249.06	-0.58	0.562
IIR-RIR x Language x Digit-Span	-2.23	13.58	-0.16	0.870
RIR-IRI x Language x Digit-Span	-8.42	13.94	-0.60	0.546
IRI-RRI x Language x Digit-Span	12.18	14.28	0.85	0.394
IIR-RIR x Language x Corsi	6.75	10.79	0.63	0.532
RIR-IRI x Language x Corsi	-13.84	11.10	-1.25	0.213
IRI-RRI x Language x Corsi	-10.95	11.34	-0.97	0.334
IIR-RIR x Language x Stroop	434.50	315.22	1.38	0.168
RIR-IRI x Language x Stroop	-56.40	324.89	-0.17	0.862
IRI-RRI x Language x Stroop	15.90	330.54	0.05	0.962

Note: ***, **, and * denote $ps < .001$, $.01$, and $.05$, respectively.