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Code-switching and cognitive control: a review of current trends and future directions

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Bilinguals frequently switch between their languages, a phenomenon known as code-switching (CS). CS is supposed to interact with cognitive control, making theories of cognitive control crucial for understanding bilinguals' CS behavior. This article reviews four prominent frameworks of cognitive control as they pertain to CS. We critically assess each framework and examine empirical studies that test their predictions. In doing so, we highlight the strengths and limitations of these models, ultimately discussing their compatibility. We conclude by proposing avenues for future research and suggesting potential pathways toward developing a comprehensive framework of cognitive control in CS.

KEYWORDS

bilingualism, code-switching, cognitive control, adaptive control hypothesis, control process model, language entropy

1 Introduction

Bilingual individuals often navigate complex linguistic environments, frequently switching between languages. This seemingly spontaneous switching from one language to another, or the mixing of elements from two languages within a single speech event is central to bilingual language use and is commonly termed "code-switching" (Appel and Muysken, 1987). CS is a multifaceted behavior studied across various disciplines, including linguistics, sociology, and, more recently, cognitive neuroscience. While linguistic research into CS primarily focuses on the structural aspects and language-specific constraints of CS, sociological research emphasizes its social and cultural dimensions. Over the past decade, there has been growing interest in understanding CS as a cognitive phenomenon, particularly in exploring the cognitive mechanisms that underlie this behavior. Despite its seemingly spontaneous nature, CS is assumed to involve complex cognitive control processes. Cognitive control—the ability to pursue goal-directed behavior—manifests through mechanisms that maintain and update information essential for task execution (Cohen, 2017). In the context of CS, cognitive control is evident in the monitoring of languages, the management of interference, and the inhibition of conflicting information. Consequently, a better understanding of these control processes can offer valuable insights into explaining bilinguals' CS behavior. Given the variation among bilinguals in context, patterns, amount, and frequency of CS, it is likely that they also differ in how they employ cognitive control, not only in comparison to monolinguals but also in relation to other bilinguals. Thus, the interaction between bilingual language use and cognitive control is arguably modulated by individual differences.

A variety of theoretical frameworks provide valuable perspectives to help advance our understanding of the role of cognitive control in CS. This review focuses on four prominent frameworks: the Adaptive Control Hypothesis (Green and Abutalebi, 2013), the (Extended) Control Process Model (Green and Wei, 2014; Green, 2018), the Dual Mechanisms of Control (Braver, 2012), and the Language Entropy Approach (Gullifer and Titone, 2021). We will start by examining each framework in detail and reviewing the relevant empirical studies. Subsequently, we will critically analyze the frameworks and the empirical studies testing their assumptions. Finally, we will summarize key insights and offer recommendations for future research, emphasizing necessity for a more comprehensive framework for cognitive control in CS, and ways in which this can be achieved.

2 Frameworks

2.1 Adaptive control hypothesis and the extended control process model

The Adaptive Control Hypothesis (ACH) stands out as a prominent framework for understanding cognitive control in bilingual individuals, particularly in the context of language switching. Green and Abutalebi (2013) look into the dynamics of speech production in bilinguals. The core proposal of the ACH posits that language control processes dynamically adapt to the recurrent demands imposed by the interactional context. Green and Abutalebi (2013) aim to illustrate a set of language control processes critical for conversation in various interactional contexts in which bilinguals typically find themselves, elucidate the relative demands these contexts impose on these processes, and explain the neural underpinnings of adaptive changes. To this end, ACH identifies eight control processes integral to bilingual speech production, categorized based on their involvement in three interactional contexts:

The interactional contexts delineated by the ACH are as follows:

1. Single-language context: In this setting, one language is used in one environment, while another language is used in another environment. For instance, a child born in Germany to Turkish parents might exclusively use Turkish at home and German at school. As such, frequent code-switching rarely occurs within this setting, as bilingual speakers typically use each language exclusively in distinct single-language contexts.
2. Dual-language context: Here, both languages are employed, although typically with different addressees. The child from the previous example might speak German with other children in his environment but switch to Turkish when talking to his sibling. Thus, in this context, language switching may occur within a conversation, depending on the interlocutor (Green and Abutalebi, 2013, p. 518).
3. Dense CS context: This context involves speakers routinely alternating between languages within a single utterance, adapting words and morphological markings from one language in the context of the other. A household where both parents and children regularly use both languages to communicate could be characterized as a dense CS context.

Green and Abutalebi (2013) identify the following control processes implicated in bilingual language production:

- Goal maintenance: The speaker must sustain an established task goal, such as consistently speaking in one language rather than switching to the other.
- Interference control: Managing potential disruptions to language use is essential for maintaining the task goal. This involves two sub-processes; *conflict monitoring,* which detects conflicts between the target and non-target languages, and *interference suppression,* which actively inhibits the non-target language.
- Salient cue detection: Recognizing cues, such as the arrival of a new conversational partner is crucial since these may signal a need to switch languages. Salient cue detection triggers three additional control processes: *selective response inhibition,* which halts an ongoing response to allow for a more task appropriate one; *task disengagement,* which stops the use of the current language; and *task engagement,* which enables a switch to the other language as needed.
- Opportunistic planning: Bilingual speakers can leverage whatever resources are immediately available to reach their communicative goals, such as adapting words from one language to fit into the syntactic frame of the other.

It is suggested that the demand on these control processes varies across different interactional contexts. When both languages are active and compete for selection, heightened demand on goal maintenance, conflict monitoring, and interference suppression are expected. However, the degree of explicit presence of the non-target language differs across contexts, affecting how interference is managed. Green and Abutalebi (2013) distinguish between how interference from the non-target language is resolved differently in different settings. In the single-language and dual-language contexts, the language task schemas are in competition, requiring interference to be managed to avoid inappropriately switching. In contrast, in a dense CS context, the task schemas of both languages are cooperative, reducing the need for interference suppression. Instead, bilinguals can engage in opportunistic planning, leveraging flexible expression options that would normally compete in the other contexts. The authors argue that the demand for goal maintenance, conflict monitoring, and interference suppression, although present in the single-language context, is most pronounced in the dual-language context. Here, speakers must constantly balance maintaining one language while being ready to switch based on external cues. Opportunistic planning, on the other hand, is most heavily taxed in dense CS contexts.

In settings where a target language is clearly defined by the interactional context, using the non-target language can result in an "interactional cost" (Green and Abutalebi, 2013). To avoid or minimize this cost, bilinguals adapt their language control processes to navigate different interactional contexts more effectively. For instance, a single language-context demands high proficiency in the conversation's language, but as proficiency in a second language increases, so does interference. Speakers must then adopt control processes to manage this interference. In a dual-language context, bilinguals aim to minimize interactional cost by maintaining focus on the target language while suppressing interference from the other. They must also remain prepared to switch languages when prompted by cues. In a dense-code switching environment, one speaker's refusal to engage in CS may raise an interactional cost due to perceived pressure from other interlocutors to stay in one language themselves, potentially leading to disengagement by conversational partners over time. Overall, the authors argue that interactional costs drive the need to develop and engage control processes specific to each interactional context, helping bilinguals avoid these costs and communicate more effectively.

Green and Abutalebi (2013) propose that exploration of the ACH requires examining performance patterns on various tasks tapping into specific language control processes through the development of efficient testing protocols. Speakers who are habitually in dense CS contexts are anticipated to exhibit fluent performance in an experimental condition where they can freely use either language. In contrast, a condition which requires language switching upon a cue is expected to result in impaired performance. Conversely, speakers from a single-language or a dual-language context are expected to demonstrate greater fluency in the cued condition where they are required to switch into, and remain in one language.

Beyond overall performance considerations, Green and Abutalebi (2013) also refer to experimental tasks targeting specific control processes. They propose that adaptive effects can be expected in reaction time analyses of conflict tasks, such as the Stroop task. In such tasks, interference effects appear to decrease for slower responses, particularly for individuals more proficient in inhibition. Consequently, the authors suggest that bilingual speakers who are typically engaged in dual-language contexts will exhibit greater proficiency in inhibition compared to those in the single-language or dense CS contexts.

Following the ACH, Green and Wei (2014) proposed the Control Process Model (CPM) of CS, offering a theoretical framework to understand how bilingual speakers manage language selection and suppression during speech production. The CPM suggests that CS is not merely the result of fluctuating activation levels within bilinguals' language networks but is governed by external control processes that regulate which items enter speech production.

The model outlines several key components: conceptual and intentional representations, language networks, language control processes, and a competitive queuing network, which consists of a planning layer and a choice layer. Activation begins with a conceptual representation that stimulates language networks for both languages, allowing access to word forms and phonological representations. The output from these networks is controlled by language task schemas, which may operate either competitively or cooperatively, depending on the communicative context. In competitive control, the task schema for the target language opens its "gate," allowing only lexical and syntactic items from that language to pass into the competitive queuing network, while the gate for the non-target language remains closed, preventing interference. By contrast, cooperative control—subdivided into coupled control and open control—enables more flexible management of linguistic items from both languages. In coupled control, the gate for one language is open

TABLE 1 Muysken (2000)'s code-switching types as observed in naturalistic speech of Turkish-German bilinguals, German marked in bold (Treffers-Daller, 2020).

CS Type	Example
Insertion	Bütün **Flughafen**'ı bul-du-m. *Entire* ***airport****-ACC. found-PAST-1.SG.* "I found the entire airport."
Alternation	On-dan sonra balo-ya git-tiğ-imiz-de **sind wir telephonieren gegangen.** *That-ABL. after balo-DAT. go-FNOM.-1.PL-LOC.* ***are we telephone gone.*** "After that, when we went to the ball, **we went out to give a call.**"
Dense CS	Und ben **feiern** yap-a-ma-dı-m, çünkü **an dem Tag wo Klassenfahrt**'a gid-ecek-ti-m, akşam-a **konnt' keine Fete machen.** *And I* ***party*** *do-ABIL.-NEG.-PAST-1.SG because* ***on the-DAT. day where school trip****-DAT. go-FUT.-PAST-1.SG evening-DAT.* ***could no party make.*** "And I could not go to the party because on the day that I was going to the school trip I could not have a party until the evening."

while the other is "on the latch" and can be temporarily pushed open when an item or structure from the non-target language becomes more appropriate. Once items pass through these gates, they enter the competitive queuing network, which organizes them into a coherent sequence for speech production. This network has a planning layer, where words and structures are initially activated, and a choice layer, where the most active items are selected in the correct sequence, ultimately leading to spoken language.

The CPM explains that the relationship between language schemas and the control modes they employ depends on the interactional context. In a single- or dual-language context, competitive control is used to prevent interference from the non-target language. In contrast, in a dense CS context, cooperative control allows speakers to draw on resources from both language networks. Green and Wei (2014) argue that different types of CS can be explained by variations in the cooperative control process that governs entry into the planning layer. They build on Muysken's (2000) CS types, namely insertion, alternation, and dense CS.[1] In the insertion pattern, there is a clear matrix language and a lexical item from another language is embedded into the structure of the matrix language, similar to lexical borrowing. Alternation refers to switching between larger chunks of speech in two languages. Unlike insertion, where there is a clear matrix language governing the structure of the sentence, alternation involves segments from two languages without a dominant matrix language for the sentence as a whole. Dense CS refers to an integration of both languages at sentence level, using both lexicon and grammar from either language (see Table 1 for examples).

In the CPM, CS is managed through cooperative control. Coupled control facilitates CS patterns like insertion and alternation by allowing the dominant, or matrix language to temporarily relinquish control to the other language. Open control, on the other hand, governance CS, reducing the cognitive costs

1 In the CPM, dense CS is used interchangeably with *congruent lexicalization* which specifically applies to language pairs that share similar grammatical structures. In its broader sense, dense CS can be realized with a wider range of language pairs, including those that are typologically distinct.

of switching languages. This flexibility minimizes the need to inhibit a previously active language schema or to overcome the inhibition of a previously irrelevant language (see also, Inhibitory Control Model; Green, 1998). The model suggests that speakers may develop habitual control strategies based on their predominant interactional environment. However, it also allows for flexibility, meaning speakers can adapt their control strategies to suit different contexts. This adaptability may result in changes in speech fluency or hesitation during transitions between control modes.

The CPM posits that speakers in a dual-language context enhance their cognitive control more than those in a single-language context, as they need to manage more frequent interference. On the other hand, speakers in a single language context exercise more than those in a dense CS context, where switching is expected. Speakers who predominantly engage in one type of interactional context are likely to develop dominant habits in language control. Nonetheless, they can still shift to different control modes as needed, despite their usual habits with these transitions, often marked by increased hesitation or slower speech. For example, a speaker from a dense CS context might hesitate more when shifting to a single-language mode, as they must override their open control strategy. In contrast, speakers from dual-language contexts, who typically operate under competitive control, may switch more smoothly between languages but with greater hesitation when returning to single-language speech. If these speakers increasingly engage in dense CS contexts, eventually an open control mode may be adopted, which minimizes hesitations over time.

Green (2018) introduced an extended version of the CPM by incorporating more detailed neurocomputational mechanisms. As an addition to the earlier model, the extended CPM acknowledges the influence of the conversational partner's speech input on CS. Besides the speaker's own speech act intention, the speech of the interlocutor can serve to prime specific words or expressions, which can then activate corresponding language networks in the bilingual speaker.

The extended CPM also diverges from the earlier model by adopting a single gate mechanism, as opposed to separate gates for target and non-target languages. The proposed sub-cortical gate is described as an active constructor of the utterance plan It interacts with frontal regions to select a syntactic structure and to bind lexical items to open slots in that construction. Plans are constructed in the planning layer of a competitive queuing network. The competitive choice layer of this network allows serial order despite the parallel activation of items in the plan.

The operation of the gate depends on the nature of the language control signals. In a single-language context, the gate blocks entry of activated items and constructions from the non-target language into the speech plan. Non-target language items are inhibited before they can compete for binding, thereby maintaining the dominance of the target language.

In CS contexts, both languages remain actively engaged and accessible for entry into the speech plan, similar to single-language contexts. However, the level and nature of this activation may differ, as CS contexts often involve a more dynamic interplay between the two languages, enabling frequent switching or blending. Under coupled control, the gate dynamically adjusts to allow for temporary shifts in control. For an insertion, the gate temporarily opens to bind an item from the non-matrix language to a role in the current clause of the matrix language. For an alternation, the gate opens to allow a phrase or clause from the non-matrix language to be incorporated into the speech plan. Green (2018) points out that insertions are the best example of coupled control due to their intra-clausal nature, whereas alternations can be mediated by coupled control or competitive control depending on whether they are intra-clausal or inter-clausal, respectively. The open control mode, which was originally associated with dense CS in structurally similar languages (i.e., congruent lexicalization), is broadened in the extended CPM to apply to a wider range of language pairs, including those that are typologically distinct.

The extended CPM also explores the potential costs associated with CS, particularly under coupled control. For example, when switching away from and then back to the matrix language, there may be a processing cost due to the need to inhibit and then reactivate the matrix language. Additionally, binding costs may arise from increased competition between items from both languages when they are simultaneously available for binding within the same syntactic frame, even when the insertion is pragmatically appropriate. The competitive queuing network continues to play a vital role in organizing the selected items into a serial order for speech production in the extended CPM. However, in the extended model, the network's function is more closely tied to the operations of the gate mechanism and the binding process, particularly in contexts involving dense CS. The network now deals with more complex interactions between languages, especially under open control, where binding costs must be managed to maintain fluent speech. Finally, the extended CPM also refers to attentional correlates of competitive and cooperative control states. Green (2018) argues that competitive language control uses the resources of a single language network and requires a narrowing of attention, which is enhanced when a speaker must use one language over another in a dual-language context. Conversely, cooperative control utilizes the resources of both language networks, and is predicted to increase the breadth of attention in bilinguals engaged in dense CS, making them more susceptible to interference. It is suggested, then, that individuals who routinely engage in dense CS may become more skilled at resolving such interference.

Since its proposal, several studies have explored the assumptions and predictions of the ACH, illuminating the interplay between bilingual interactional contexts and cognitive control. In addition to the ACH, many of these studies also take the (extended) CPM as a frame of reference.

Hartanto and Yang (2016) investigated whether the typical interactional contexts of bilinguals influenced their performance on a color-shape task-switching task. In this task, participants were required to respond to either the color or shape of a target based on the given cue, with trials alternating between task-switch trials (where a switch occurred between color and shape) and task-repeat trials (where the task remained the same). Their findings showed that bilinguals who self-reported frequent engagement in dual-language context exhibited smaller switch costs, measured by faster reaction times during task-switch trials, compared to those from single-language context backgrounds. In a subsequent study by Hartanto and Yang (2020), the dual-language context emerged as a significant predictor of task-switching, consistent with the predictions of both the ACH and the CPM that dual-language context would adaptively enhance bilinguals' task-switching abilities. While in contrast and as opposed to the predictions of both frameworks, the dense CS context, and not the single- or dual-language contexts, significantly predicted inhibitory control and goal maintenance. In addition, they found that bilinguals' self-reported unintended language-switching tendency (Bilingual Switching Questionnaire: Rodriguez-Fornells et al., 2012) predicted poorer performance on task-switching.

Struys et al. (2019) focused on the impact of bilingual experiences on the interplay between language switching and domain-general control. Their study, involving Dutch–French bilingual young adults, employed a bilingual semantic categorization task with unpredictable language switches to assess language switching abilities and the Simon task to assess domain-general control. The categorization task required participants to respond as quickly as possible to the animacy of the stimulus which could be in either language. Results indicated a correlation between global response times on the Simon task and the forward switch cost (from first to second language) in the categorization task. Furthermore, the forward switch cost was linked to recent language exposure rather than the age of acquisition of the second language (L2), which the authors interpreted in support of the ACH as an indication of short-term adaptability of language control to demands from the language environment.

In a large sample of Polish-English bilinguals, Kałamała et al. (2020) adopted a latent variable approach to test the ACH prediction that a dual-language context is associated with more efficient response inhibition. Contrary to expectations, their results offered no support, and instead suggested that bilinguals who are habitually in dual-language contexts either do not engage response inhibition to control language production or engage it to the same extent as other bilinguals. The authors concluded that the ACH may not adequately explain the discrepancy observed in studies testing the relationship between bilingualism and cognitive control efficiency, at least concerning response inhibition.

In their investigation of the interplay between language switching behavior, interactional contexts, and cognitive control in bilinguals, Lai and O'Brien (2020) discussed their results within the ACH framework. Their findings offered partial support for the framework, whereby higher reported engagement in the dual-language context was positively associated with cognitive engagement and disengagement on verbal tasks. Additionally, non-verbal goal maintenance and interference control were linked to un-cued inter-sentential language switching.

In a parallel vein, Beatty-Martínez et al. (2020) hypothesized that differential patterns of association between language and cognitive control might emerge for different interactional contexts. In order to test their hypothesis, they employed the AX-CPT along with two lexical production tasks to explore the consequences of differing interactional contexts on the modulation of cognitive resources and language abilities in bilinguals. They found that the way bilinguals accessed lexicons in each language and its relationship with cognitive control was contingent on their interactional contexts of language use.

Ng and Yang (2022) investigated the differential impact of bilinguals' CS patterns on various aspects of cognitive control. In addition to self-report questionnaires and EF tasks which tap into interference control and salient cue detection, the study involved a "verbal opportunistic planning task" in which participants were asked to complete various sentences with words that best fit the context, as quickly and accurately as possible. Their findings partially supported the ACH, and showed that bilinguals who predominantly engaged in alternation (i.e., dual-language context bilinguals) did not perform better in interference control, salient cue detection, or planning in terms of accuracy, but exhibited advantages in opportunistic planning in terms of RT. Bilinguals who predominantly engaged in insertion and congruent lexicalization (i.e., dense CS context bilinguals) showed disadvantages in interference control and salient cue detection, but advantages in opportunistic planning in both RT and accuracy.

Han et al. (2022a) investigated how different interactional contexts modulate cognitive control in Chinese–English bilinguals during bilingual language comprehension. Their results indicated that both the dual-language and Chinese single-language contexts significantly enhanced participants' inhibitory control efficiency. In a related investigation, Han et al. (2022b) explored the influence of CS habits on cognitive shifting and inhibition. The study revealed that frequent bilingual switchers demonstrated reduced effort and time costs in various verbal and non-verbal switching tasks. Additionally, individuals engaged intensively in dense CS practices exhibited superior conflict monitoring and inhibition skills in a Go/No-go task. The authors concluded that while a connection was observed between the intensity of single-language context experience and goal maintenance efficiency in alignment with the ACH and the CPM, dense CS experience unexpectedly exhibited a facilitatory effect on response inhibition proficiency which contrasted the predictions of these frameworks.

In a more recent study, Gosselin and Sabourin (2023) examined whether CS in a dual-language interactional context may enhance inhibitory control in a sample of French Canadian bilinguals. They found that dual-language bilinguals who reported more habitual French-to-English (but not vice versa) switching exhibited better domain-general goal-monitoring and inhibition abilities indexed by a Flanker task. However, CS was associated with language-specific inhibition skills measured by a bilingual Stroop task only when it was deliberate. Self-reported frequent unintentional CS (Bilingual Switching Questionnaire: Rodriguez-Fornells et al., 2012) on the other hand was associated with reduced inhibition skills. Based on these findings, the authors suggested that dual-language code-switchers may experience enhanced inhibitory control, but only when their switching is intentional.

In summary, the Adaptive Control Hypothesis (ACH) and the Control Process Model (CPM) offer valuable frameworks for understanding the relationship between CS, interactional contexts, and cognitive control. The studies exploring these frameworks highlight this complex interplay. Some studies provided support for the frameworks, including a positive relationship between dual-language contexts and task-switching abilities (e.g., Hartanto and Yang, 2016, 2020; Lai and O'Brien, 2020), as well as goal maintenance and inhibitory control (e.g., Han et al., 2022a; Gosselin and Sabourin, 2023). Others either did not support the predictions of these frameworks (e.g., Kałamała et al., 2020; Ng and Yang, 2022), or presented findings that contradicted them (e.g., Hartanto and Yang, 2020; Han et al., 2022b). Overall, findings indicate that the impact of bilingual experiences on cognitive control is context-dependent, with performance variations linked to individual code-switching habits. We revisit these diverse findings and their relevance in the discussion section.

2.2 Dual mechanisms of control

The dual mechanisms of control (DMC) (Braver, 2012) which was originally developed to explain domain-general cognitive control, has gained relevance in the study of language-specific phenomena, particularly CS, where inhibition and monitoring are essential. Researchers have increasingly applied the DMC framework to better understand the cognitive control mechanisms involved in CS.

In its essence, DMC framework posits that cognitive control functions through two distinct modes known as “proactive control” and “reactive control.” According to this framework, the variability in individuals’ capacity to regulate their thoughts and actions to achieve behavioral goals can be attributed to differences in the temporal dynamics between these two control modes. DMC framework further explains three sources of variation in cognitive control function, encompassing intra-individual, inter-individual, and between-group differences.

Proactive control, identified as an “early selection” mechanism, involves the active maintenance of goal-relevant information before encountering a cognitively demanding event. This mode of control is employed to bias attention, perception and action systems in a goal-driven manner, depending on anticipating and preventing interference before it arises. Proactive control functions as a top-down bias source that facilitates the processing of upcoming events, but its utilization is contingent upon a favorable cost/benefit tradeoff, acknowledging the salience efficacy of this control mode. Engaging proactive control relies on the availability of strong reliable contextual cues that are capable of triggering goal activation and maintenance in advance. While proactive control enables continuous adjustments of plans and behaviors to successfully achieve goals, it demands ongoing goal maintenance, making it highly resource-consuming. Consequently, the activation of proactive control consumes a substantial portion of one’s attentional capacity, reducing available capacity for maintaining other information within working memory.

Reactive control operates as a form of “late correction,” coming into play as needed, particularly following a high-interference event. This cognitive control mode relies on the detection and resolution of interference after its onset, reflecting a bottom-up reactivation of task goals. In contrast to proactive control, under reactive control, goal representations are activated only when necessary. The computational efficiency of reactive control lies in its ability to free up resources during the interval between goal formation and completion, enhancing the effective execution of other tasks. However, this strategy necessitates repeated reactivation of the goal instead of continuous maintenance. Reactive control is more dependent on the salience and discriminative nature of a stimulus, as they drive the reactivation process. In contrast to proactive control, reactive control is stimulus-driven and transient, and does not rely on contextual cues in advance of the time. This characteristic makes fewer demands on attentional resources and commitment. Nevertheless, due to its stimulus-dependent and late-acting nature, reactive control is more susceptible to transient attentional capture or orienting effects that may disrupt goal reactivation when needed.

Regarding the sources of variation in cognitive control function, Braver (2012) suggests that on an intra-individual level, subtle differences in similar tasks can lead to significant changes in the preferred cognitive control strategy. It is proposed that a low expectancy of an event and a high expected memory load result in the recruitment of reactive control, whereas a high expectancy of an event and a low expected memory load lead to the mobilization of a proactive control strategy.

At the inter-individual level, the adoption of proactive control is tied to cost-benefit considerations, which weigh the ease of actively maintaining goal representations in advance against perceived value of the consequences associated with such a control strategy. Hence, individual cognitive differences, including the efficacy of active goal maintenance in working memory and fluid intelligence, can significantly influence the propensity to use proactive control. Additionally, individuals with a high sensitivity to rewards tend to employ proactive cognitive control strategies to optimize their performance in various task-switching scenarios. Group differences manifest as reduced utilization of proactive control in older adults, young children, and individuals with schizophrenia compared to other groups.

Braver (2012) provides examples of reactive and proactive control using the classic Stroop color-naming task. Reactive control relies on the detection of interference following the presentation of an incongruent stimulus. During reactive control, task goals are not actively maintained between trials and may not be triggered by congruent stimuli. This mode often results in accurate responses on incongruent but at the expense of slower response times. Proactive control, conversely, involves sustained active maintenance of task goals during intertrial intervals. While this mode minimizes conflict and leads to faster response times for incongruent stimuli, it presumably comes with a higher cognitive load between trials.

Braver (2012) highlights the AX-CPT paradigm, a recent adaptation of the continuous performance task (CPT; Rosvold et al., 1956) as a key tool for investigating proactive and reactive control. In the AX-CPT, participants are instructed to press one button when a target stimulus appears (an X preceded by an A, i.e., AX trials) and a different button for any other stimulus. The task manipulates the frequency of target and non-target trials, with contextual cues shaping participants’ expectations. For example, a BX trial (X preceded by B) can strongly, but incorrectly, prompt participants to respond as if it were a target. On the other hand, contextual cues preceding the probe can generate expectations about the upcoming stimulus. While these expectations are useful for responding correctly to BX probes, they can lead to errors on AY trials, where A is followed by a non-target Y. Within the DMC framework, proactive control involves using cues to anticipate responses, while reactive control focuses on adjusting responses based on the presented stimulus and resolving any conflicts that arise. DMC initially found relevance in bilingualism research in comparisons of processing efficiency between bilinguals and monolinguals. Morales et al. (2013) utilized the AX-CPT task to demonstrate that bilinguals outperformed monolinguals in conditions requiring substantial adjustments of proactive–reactive control. It was seen that although bilinguals employed proactive control whereby they monitored and paid attention to the context cue, they were also able to use inhibitory (i.e., reactive) control when the context provided incongruent information. Subsequently (Morales et al., 2015), the authors replicated these findings incorporating event-related potential (ERP) activation related to probe processing which showed that although both bilinguals and monolinguals relied on context information, bilinguals were able to apply higher reactive control when it is necessary to override competing cue-information. The authors concluded that bilinguals' processing efficiency arises from the interplay between proactive and reactive control rather than the exclusive engagement of one process.

More recently, research has taken a DMC approach to CS, based on the assumption that deployment of proactive and reactive control may depend on the interactional context, the bilingual's habitual CS behavior or CS patterns used. Bilinguals in single-language contexts may be more likely to rely on reactive control to address rare, unexpected demands for the non-target language. In dual-language contexts, bilinguals anticipate both languages across interactions but expect only the target language when conversing with a specific interlocutor. Individual differences may influence their approach: some may adopt proactive control to keep both languages accessible for seamless switching, while others may favor reactive control, reducing working memory demands and reactivating the non-target language only when prompted. In dense CS contexts, where frequent and dynamic switching is the norm, proactive control might be utilized to anticipate frequent switches, while reactive control resolves conflicts arising from unexpected interference.

Different types of CS may also engage these control modes to varying degrees. Insertion, which involves embedding smaller linguistic units from one language into another, primarily engages reactive control because the switch is not pre-planned but occurs spontaneously due to lexical salience or accessibility, requiring bilinguals to suppress interference from the dominant language at the moment of retrieval. Alternation, in contrast, relies more on proactive control, as speakers anticipate language shifts and maintain activation of both linguistic systems to ensure coherence. Dense CS, where bilinguals fluidly integrate both languages within a single utterance, involves a dynamic interplay of both control modes. While proactive control may help in anticipating frequent switches, reactive control is continuously engaged to resolve linguistic interference at the phrase and word levels. This distinction is crucial, as it aligns with the broader discussion of interactional contexts influencing cognitive control, where speakers in different language environments develop habitual reliance on either proactive or reactive control strategies.

In one of the earlier studies adopting a DMC perspective on CS, Beatty-Martínez et al. (2020) used the AX-CPT to test their hypothesis that control processes associated with proactive control trigger the strongest adaptive response to environmental demands of the varied (akin to dual-language) context. Their results showed that on average bilinguals from the varied context showed greater reliance on contextual information, favoring engagement of proactive control processes, whereas separated (akin to single-language) context bilinguals tended to minimally rely on context processing, favoring engagement of reactive control processes. Performance for bilinguals from the integrated (akin to dense CS context) context fell somewhere in between the other two groups. Thus, the authors suggested that being bilingual alone is not associated with a specific pattern of cognitive control, rather it is the context of habitual language use which plays a major role.

Hofweber et al. (2020) explored how different types of CS modulated various aspects of executive functioning using a Flanker task. They used a frequency judgment task involving insertion, alternation, and dense CS to measure participants' CS habits. Bilinguals who stated to engage more in alternation type of CS displayed inhibitory advantages in conditions inducing reactive control while those engaged in dense CS performed better at proactive monitoring conditions. Bilinguals, overall, outperformed monolinguals in executive functions aligning with their most frequent CS habits. The authors proposed that processing models of CS processing should incorporate a dual control mode perspective.

Kheder and Kaan (2021) investigated the impact of daily dense CS frequency and L2 proficiency on cognitive control efficiency in the Simon task. Results showed that frequent code-switchers made fewer errors and demonstrated improved accuracy rates. However, L2 proficiency interacted with CS frequency in modulating response times across trials. Highly proficient frequent code-switchers exhibited better conflict adaptation suggesting superior dynamic adjustment of inhibitory and monitoring processes in line with the task goal. Drawing insights from Morales et al. (2013, 2015) interpretation of the DMC framework, the authors concluded that frequent code-switchers, particularly those with high L2 proficiency, excel in dynamically adapting inhibitory and monitoring processes, enhancing overall cognitive control efficiency.

More recently, Jiang et al. (2023) used a self-paced reading task comprising alternation and dense CS conditions to test whether experimentally induced intra-sentential CS types influence the engagement of cognitive control in L1-dominant bilinguals' language control during comprehension. They assessed language switch cost as a marker of reactive control and reversed language dominance effects as a marker of proactive control, and examined how these language control measures related to domain-general inhibition and monitoring capacities as indexed by a Flanker task. The results showed a larger switch cost in the alternation condition compared to dense CS condition. Moreover, bilinguals' inhibition skills were associated with the switch cost in the alternation context, while monitoring was associated with the language dominance effect in dense CS context. These findings suggest that alternation poses a high demand for reactive inhibition whereas a dense CS context is more likely to prompt proactive monitoring during comprehension. As such, the authors concluded that alternation and dense CS trigger different aspects of cognitive control during comprehension.

In summary, the DMC framework provides insights into cognitive control in bilinguals, particularly regarding CS. Whereas, some studies associated certain interactional contexts or CS habits with either reactive or proactive control (e.g., Beatty-Martínez et al., 2020; Hofweber et al., 2020; Jiang et al., 2023), others found that bilinguals often utilize a combination of these control mechanisms, with their performance influenced by their CS habits and the interactional context (Morales et al., 2015; Kheder and Kaan, 2021). These discrepancies in findings will be further addressed in discussion.

2.3 Language entropy approach to bilingualism

Gullifer and Titone (2021) present a pioneering cognitive-linguistic framework that redefines the understanding of bilingual experiences by focusing on the element of uncertainty. Instead of treating bilingualism as a distinct subset of language processing, their approach strives to encompass the entire spectrum of language use, ranging from monolingual to multilingual, with a primary focus on the crucial role of uncertainty. They assert that bilingual environments inherently entail fluctuating language demands, giving rise to a spectrum of cognitive, linguistic, and social uncertainties. Bilingual individuals, in turn, must navigate and adapt to these uncertainties through the engagement of neurocognitive systems responsible for language and cognitive control.

Gullifer and Titone (2021) suggest that bilinguals experience uncertainties that go beyond those that manifest within a single language, such as linguistic ambiguities at various levels of representation, as evidenced in studies employing forced language switching tasks, which reveal processing costs associated with language switches compared to non-switch trials. While conventional explanations attribute these costs to cognitive control processes like inhibition, the language entropy approach posits a connection to language-related uncertainty. Gullifer and Titone (2021) propose that a language switching task within an experimental context is inherently marked by high uncertainty for participants, although the probability of switching becomes discernable as the task unfolds. In contrast, naturalistic language switching tends to adhere to distinct patterns in bilingual communities, thereby mitigating uncertainty. Furthermore, they suggest that factors such as increased time allocated to process the switch, the ability to switch voluntarily, switches embedded in sentence context, and patterns resembling those in the community can be viewed as mechanisms that reduce uncertainty.

Central to their uncertainty-based approach is the incorporation of the concept of "entropy." Entropy, in this context, serves to quantify the degree of uncertainty within a system or the capacity of a system to convey information. In practical terms, a highly likely event imparts minimal surprise and little information, whereas an unlikely event is more surprising and carries a higher informational load. Gullifer and Titone (2021) extended this notion to introduce the concept of "language entropy" as a measure of language-related uncertainty for individuals or environments. They posit language entropy as a continuous index, reaching its minimum when a single language dominates all the time and peaking when the usage of two languages is equal in a given context (Gullifer and Titone, 2019). As such, language environments where one language is relatively unlikely to be used is categorized as "low entropy" language environment, whereas situations where both languages are likely are suggested to be "high entropy" contexts.

In delineating how CS fits with the idea of language entropy, Gullifer and Titone (2021) note that "not all bilinguals code-switch, even if they are continually exposed to (...) high entropy linguistic environments" (p. 480). They suggest that bilinguals who habitually engage in high entropy situations develop attractor states in order to reduce internal entropy. Whereas, some bilinguals may attract to a particular language state, and stay in that language by default; others may attract to a bilingual state leading to switching between interlocutors or context, or a CS state that involves dense CS.

Prior to the proposal of the framework, Gullifer et al. (2018) investigated resting-state functional connectivity among French-English bilinguals. They found that higher entropy in social language use was associated with greater connectivity between regions involved in language control, particularly between the anterior cingulate cortex and the putamen, as well as with increased reliance on proactive control in the AX-CPT completed outside the scanner. Drawing on findings from preliminary work (Gullifer et al., 2018, 2021), the authors proposed a correlation between individual differences in language entropy and neurocognitive aspects of executive control and language proficiency. These findings imply that language-related uncertainty exerts an influence on the neurocognitive systems responsible for language and cognitive control.

The language entropy approach, despite being a relatively recent proposition, has received substantial interest and undergone considerable empirical testing. In a study by Li et al. (2021), bilinguals' executive functions were examined using language entropy, defined as "language diversity across social contexts." Employing neuroimaging techniques, they explored whether variations in language experience among bilinguals were linked to brain functional network patterns determined by performance in executive control tasks. The results indicated that individuals with higher language demonstrated increased brain network specialization and segregation and lower signal variability, which were associated with better performance in monitoring, task switching, and goal maintenance, but poorer performance in inhibitory control as indexed by the Stroop effect.

In another study, van den Berg et al. (2022) utilized language entropy to measure bilinguals' language usage patterns and explored its association with executive control, as measured by performance on a color-shape switching task. Language entropy was calculated based on two contexts: university and non-university. Pupillometry was recorded during task performance as a supplementary measure. Results revealed that bilinguals with more compartmentalized language use in non-university contexts exhibited larger switch costs as shown by a larger difference in pupil dilation for switch trials compared to non-switch trials. Moreover, bilinguals with higher diversity in language use in non-university contexts showed reduced mixing costs. However, no significant interactions were found between language entropy in either context and switching cost in the behavioral data.

Wagner et al. (2023) aimed to investigate whether and how the construct of language entropy, formulated in the highly bilingual city of Montréal, would apply in Toronto, a predominantly single-language context. Following the procedures of the original study, bilingual speakers of various languages were assigned entropy scores and underwent the AX-CPT. Performance in the task did not show an association with entropy scores, in contrast to the findings from Montréal, highlighting the role of interactional contexts play a role in determining whether language entropy correlates with cognitive task performance.

3 Discussion

3.1 Adaptive control hypothesis

Interactional contexts are central to the ACH. Consequently, for studies related to the ACH, it is crucial to accurately discern speakers' CS habits. The use of terms like "frequent/infrequent switchers" (e.g., Han et al., 2022b), "frequency of CS," "amount of CS," is commonplace in ACH studies. However, the lack of clear definitions for these terms introduces ambiguity. Clearly defining these terms is crucial, as there is no consensus in the literature regarding their interpretation, contributing to inconsistencies in results.

An important point to consider is the intentionality of CS. Hartanto and Yang (2020) administered the Bilingual Switching Questionnaire (Rodriguez-Fornells et al., 2012) to assess "unintended switching" which refer to "involuntary and inappropriate language switching that reflects accidental speech errors" (Rodriguez-Fornells et al., 2012). Their findings showed that self-reported unintended switching predicted deficits in task-switching, while a dense CS context was not linked to task-switching performance. Based on this, they argue that the relying on the general frequency of code-switching is not ideal, as it overlooks the distinction between intended and unintended switches. They also suggest that the frequency of intra-sentential CS is not a reliable indicator for a dense CS context, as it may be influenced by task-switching deficits tied to unintended switching. Gosselin and Sabourin (2023) used the same questionnaire and distinguished between intentional and unintentional code-switchers. Supporting the significance of the intentionality of CS, self-reported intentional and unintentional code-switchers performed differently on a language-specific inhibitory control task, whereby unintentional CS was associated with reduced inhibition skills.

As introduced in Section 2.1, one control process involved in a dense CS context as proposed in the ACH is "opportunistic planning," whereby speakers make use of readily available linguistic means to achieve a goal. Opportunistic planning involves adapting the words of one language to fit into the syntactic frame of another (Green and Abutalebi, 2013). This process, they argue, may occur in general speech, with bilinguals incorporating items based on current syntactic constraints, irrespective of their language membership. Furthermore, it is suggested that opportunistic planning may be inherent in everyday conversational practice, where speakers utilize previously primed phrases rather than formulating new ones due to their ready availability.

The authors emphasize a key distinction between proficient and less proficient bilingual speakers in how they "opportunistically plan" their utterances. Highly proficient bilinguals exhibit flexible use of both languages through opportunistic planning, while less proficient speakers rely on this behavior due to a lack of suitable linguistic resources in one language. This difference suggests that two speakers who appear similar in the "quantity" of their CS (i.e., how much they code-switch), may actually be employing distinct cognitive control processes. This distinction in the "motivation" behind CS can provide a foundation for refining and standardizing the terminology in the CS literature, which would enhance research on cognitive control in CS. Additionally, rethinking the "frequency of CS" (i.e., how often one code-switches) could also incorporate this contrast, accounting for the difference between speakers who code-switch flexibly by making use of available means, and those who do so out of necessity due to a lack of linguistic resources. In addition to self-report questionnaires, tasks that directly assess linguistic opportunistic planning, such as the one by Ng and Yang (2022) could be utilized to distinguish strategies employed by proficient and less proficient speakers. Furthermore, conversation analyses can reveal potential differences between these two groups in the linguistic patterns which results from opportunistic planning. For instance, typical bilingual interactions of highly proficient speakers may involve more morphological integration in both directions, and insertions may only be utilized in cases where the inserted item does not have a direct counterpart in the matrix language; whereas less proficient speakers may only engage in switching from their less proficient to more proficient language, and use insertions more frequently. It can be assumed that bilinguals in dense CS contexts employ various CS patterns such as insertion, alternation, and congruent lexicalization to varying extents, leading to considerable high intra- and inter-individual variability even among individuals with similar proficiency levels. Consequently, dismissing this variability when discussing dense CS is implausible. Hartanto and Yang (2020) argue that their finding of better inhibitory control and goal maintenance in bilinguals from dense CS contexts may be influenced by their operationalization of the dense CS context, which includes both dense CS (i.e., congruent lexicalization) and insertion. They suggest that the improved cognitive control observed in their sample could be attributed to the more frequent use of insertion type CS rather than dense CS itself. Thus, merely categorizing all bilinguals who are habitually situated in dense CS contexts as identical, based solely on the frequency or extent of their CS, oversimplifies the nature of their language use. For instance, overlooking the distinction between a bilingual in this context, who frequently engages in CS through insertions, and another who engages in CS infrequently but nonetheless adeptly utilizes congruent lexicalization would be a pitfall. (cf. Cedden et al., 2024). Thus, when evaluating the frequency of CS, it is crucial to consider not only how often to what extent a speaker engages in CS but also to identify the specific patterns they exhibit. Additionally, it is important to explore whether these patterns are linked to individual differences such as proficiency levels as suggested by Green and Abutalebi (2013).

3.2 (Extended) control process model

As introduced in Section 2.1, CPM posits that single and dual-language contexts require competitive control, whereas a dense CS context relies on cooperative control, which is further divided into open and coupled control. Insertion is considered a prime example of coupled control due to its intra-clausal nature, while congruent lexicalization (or dense CS, in the extended CPM) is achieved through open control. Alternation, depending on its structure presents two possibilities: intra-clausal alternation, where the gate opens to select a phrase or clause from the non-matrix language, is facilitated by coupled control, while inter-clausal alternation is consistent with competitive control (Green, 2018, p. 7). Thus, while intra-clausal alternations aligns with cooperative control, like dense CS, inter-clausal alternation is governed by competitive control, as in single- and dual-language contexts.

A potential factor contributing to contradictory results in the literature is the way the same terminology is sometimes used to describe different CS phenomena. For example, In Muysken's (2000) definition, alternation refers only to intra-sentential switches and does not include language switches between sentences, meaning the (extended) CPM primarily concerns itself with intra-sentential code-switches. This raises the issue of terminology and operationalization across different frameworks and empirical studies. For instance, Ng and Yang (2022), combined insertion and congruent lexicalization scores to create a dense CS index while classifying bilinguals who predominantly alternated as dual-language context bilinguals. Their assessment for alternation included both inter-sentential switches and those within a conversation. In contrast, other studies (Hofweber et al., 2020; Jiang et al., 2023) only considered intra-sentential alternation. This variation in definitions highlights the need for greater clarity regarding the term "alternation," which can encompass several forms (see Muysken, 2013):

a. Intra-clausal alternation.
b. Inter-clausal alternation.
c. Inter-sentential alternation in a dense CS context (in addition to intra- and inter-clausal alternation).
d. Inter-sentential alternation in a dual-language context.

Future research on bilingual cognitive control could benefit from addressing these distinctions more explicitly. Differentiating between inter- and intra-clausal alternation in particular may help refine our understanding of the cognitive processes underlying language use. Additionally, exploring distinctions between inter-sentential alternations with one interlocutor in a dense CS context and those with different interlocutors in a dual-language context could offer insights into the varying control mechanisms involved.

A second point of consideration in the CPM relates to the concept of open control. In delineating the concept of open control, Green (2018) introduces the criteria of "most active" and "most appropriate" as conditions for the inclusion of an item from either language into the speech plan. However, it is crucial to acknowledge that what is considered most active may not necessarily align with what is deemed most appropriate at a given moment (cf. Cedden et al., 2024). In light of this, two distinct strategies emerge: one entails immediate acceptance of the most active item, irrespective of its relative appropriateness, while the other involves a mental search to identify the most appropriate item, disregarding its current level of activity. Furthermore, the use of these strategies may be contingent upon not only the individual's proficiency, but also language processing strategies, cognitive flexibility, and communicative goals. Some speakers may prioritize the activation level of linguistic items, opting for the immediate inclusion of the most active ones into their speech plan, regardless of their relative appropriateness. This approach could reflect a preference for immediate production and may be observed in individuals who prioritize fluency and rapid speech output. Conversely, other speakers may prioritize the appropriateness of items, engaging in a deliberate search for the most suitable option, irrespective of its current activity level. This strategy could suggest underscore a focus on accuracy and precision in language production, typically observed in individuals who prioritize linguistic correctness and contextually appropriate expression. This assumption may be tested through tasks involving sentence completion (e.g., Ng and Yang, 2022), which account for both accuracy and response time. In Ng and Yang (2022), sentences were designed so that the most contextually appropriate answer required the use of expressions from a different language. A task involving a continuum of alternative answers, varying in their "appropriateness" and ease of access, could help uncover individual differences in open control strategies. Alternatively, these strategies could be assessed through acceptability judgment tasks, where individuals evaluate bilingual speech containing various code-switches and rate how appropriate or acceptable they find each instance. Last but not least, self-reports related to meta-linguistic awareness or personal opinions on CS could complement these tasks by providing additional perspectives on individual differences in control strategies and attitudes toward bilingual language use.

3.3 Dual mechanisms of control

Studies exploring the DMC framework within the scope of bilingualism thus far showed support for a bilingual advantage with regards to the flexible adjustment of proactive and reactive control processes as required in a given situation (Morales et al., 2013, 2015; Kheder and Kaan, 2021). As far as CS is concerned, the results are more mixed, partly due to a lack of consensus on terminology. Beatty-Martínez et al. (2020) concentrated on habitual interactional contexts and found that bilinguals from single-language contexts relied more heavily on reactive control as opposed to those from dual-language contexts who favored proactive control processes, whereas the dense code-switchers on average did not rely strongly on one or the other. It is important to note that, Beatty-Martínez et al. (2020) did not allude to different CS patterns of the individuals in the dense CS group, which potentially variably characterize their language use and the cognitive control processes involved, as discussed in the section on ACH. Hofweber et al. (2020) and Jiang et al. (2023), on the other hand, built their hypotheses upon intra-sentential CS, and did not discuss habitual interactional contexts. Hofweber et al. (2020) contrasted alternation and insertion with dense CS, whereas Jiang et al. (2023) referred to alternation and dense CS as both CS types and contexts. Both studies found results that are similar on the surface, suggesting a link between alternation and reactive control, and between dense CS and proactive control. However, Hofweber et al. (2020) based these links on self-reported measures of how frequently bilinguals engage in each CS type, whereas in Jiang et al. (2023) explored the engagement of cognitive control in comprehension of experimentally induced CS, involving different patterns.

While the DMC framework suggests that proactive control involves sustained goal maintenance and reactive control engages on-demand inhibitory processes (Braver, 2012), the findings by Hofweber et al. (2020) provide an alternative perspective on how different types of CS engage these control mechanisms. Specifically, their study found that bilinguals who frequently engaged in alternation-type CS showed advantages in inhibitory tasks that required reactive control, whereas bilinguals who engaged in dense CS performed better in proactive monitoring conditions. At first glance, these results seem to challenge the assumption that alternation aligns more with proactive control, as alternation requires speakers to anticipate language switches across clauses. However, Hofweber et al. (2020) argue that alternation is cognitively effortful because it requires inhibitory control to suppress interference when shifting between languages for larger speech segments. In contrast, dense CS involves frequent shifts between languages at the lexical level, requiring continuous monitoring and dynamic engagement of proactive control to anticipate and resolve interference on an ongoing basis. These findings highlight the need for an exact interpretation of proactive and reactive control within bilingual speech production. It is possible that different levels of linguistic co-activation and inhibitory demands across CS types modulate the control mechanisms at play. For instance, alternation may require a reactive inhibitory process at switch points, rather than sustained proactive control, because bilinguals maintain language separation until a switch is needed. On the other hand, dense CS involves a continuous interplay of both languages, requiring proactive monitoring to manage linguistic interference over an extended period. Furthermore, methodological differences may account for the observed discrepancies. Hofweber et al. (2020) used a flanker task designed to differentiate reactive from proactive monitoring conditions, whereas many studies linking alternation with proactive control focus on production-based paradigms that assess goal maintenance rather than inhibitory load at switch points. Future research should further investigate how task demands and bilingual profiles influence the engagement of control mechanisms during CS. By incorporating insights from Hofweber et al. (2020), we propose that CS types engage different control modes dynamically rather than fitting into a strict proactive/reactive dichotomy. This aligns with recent perspectives suggesting that bilingual language control is highly adaptable, modulating between proactive and reactive strategies based on task demands, interactional contexts, and individual bilingual experiences (Green and Abutalebi, 2013; Beatty-Martínez et al., 2020).

Overall, adopting a DMC approach to CS, particularly with respect to ACH's interactional contexts, can help contribute to a more nuanced understanding. In single-language contexts, the individual has minimal expectations for a situation requiring a switch into the non-target language. Proactive control, which relies on the availability of strong contextual cues and continuous goal maintenance, is resource-intensive and less necessary in these contexts. Instead, individuals can remain in a reactive control mode, allowing goal representations for the non-target language to be activated only when necessary—such as in the rare event of an unexpected demand for the non-target language. This reactive control strategy conserves cognitive resources while still permitting effective response to the occasional intrusion of the non-target language. In dual-language contexts, however, the individual anticipates the need to use both languages interchangeably, requiring a proactive control strategy to maintain both languages at a heightened activation level. Proactive control ensures that goal representations for both languages are readily accessible, facilitating seamless switching as soon as the situation necessitates it. This strategy demands continuous monitoring and allocation of attentional resources to support rapid switches and minimize interference.

The applicability of the DMC framework to dense CS contexts require further elaboration. Dense CS contexts involve a highly dynamic interaction between languages, where language boundaries are fluid, and both languages remain highly co-activated throughout discourse. This presents a unique cognitive challenge requiring a hybrid engagement of proactive and reactive control mechanisms. In dense CS contexts, multiple factors are at play. Both languages are anticipated at any given time; thus, proactive control is employed to maintain readiness for the potential use of either language (see Hartanto and Yang, 2020). This enables bilinguals to switch flexibly and efficiently, ensuring seamless communication. Even if only passively exposed to CS, both language networks remain highly activated in this context. One factor to consider in dense CS contexts is the intentionality of switches. In single- and dual-language contexts, it is easier to pinpoint intentionality due to the clearer need for interference control. However, in dense CS contexts, the reduced need for interference suppression makes it harder to identify intentionality, complicating the assumption of a distinct, single mode of control. The type of CS used in the context also plays a role. Over time, as an individual interacts with a particular interlocutor, patterns may emerge: If the interlocutor typically alternates languages over longer stretches or uses insertions within a clear matrix language, reactive control may be employed. In contrast, more frequent alternations or dense CS will be more effectively facilitated by proactive control. Recent research (Hofweber et al., 2020) suggests that bilinguals engaged in dense CS demonstrate enhanced proactive monitoring skills, which may stem from their experience in navigating continuous linguistic co-activation. This contrasts with bilinguals who engage more in alternation, where the need for goal reactivation at switch points fosters a more reactive control advantage. These findings indicate that dense CS fosters a control mode that is distinct from both single-language and dual-language contexts, highlighting the need for a more dynamic perspective within the DMC framework. Thus, rather than viewing proactive and reactive control as mutually exclusive, dense CS contexts suggest that bilinguals develop a hybrid control mechanism, flexibly engaging both control modes as required by the linguistic and cognitive demands of their environment. Future research should explore how these adaptive processes unfold over time and whether bilinguals engaging in dense CS exhibit distinct neurocognitive profiles compared to those in dual-language or single-language contexts.

All in all, as discussed earlier, reaching clarity and consensus of CS terminology, as well as in approaches to measuring CSappear to be of utmost priority in research investigating the DMC framework in the context of CS as well. While the DMC provides a good basis for exploring cognitive control in bilinguals, it is important to not only take into account the interactional contexts individuals are typically engaged in, but to also consider the frequency and the variability with which they engage in (dense) CS, in order to provide a clearer picture of whether and how insertions, alternations and congruent lexicalization differ in terms of the mode of control they employ. Another important distinction to consider lies in whether individuals are tested on a linguistic or non-linguistic EF task, and whether the modes of control that the individuals rely on differ between the two. Additionally, in linguistic tasks, consideration should be given to whether the task involves production or comprehension of CS. Last but not least, the distinction between habitual CS and experimental/task-dependent CS should be clear for a reliable account of the dual mechanisms of control involved in CS (see Beatty-Martínez et al., 2018 for a discussion).

3.4 The language entropy approach

The language entropy approach to bilingual language use is partly in line with the ACH and the CPM in that it suggests that bilingual environments inherently entail fluctuating language demands, leading to a spectrum of uncertainties which bilingual individuals must adapt to. It differs from the former two, however, by focusing on language use as a spectrum from monolingual to multilingual, rather than considering bilingualism as a monolithic subset of language processing strictly distinct from monolingualism.

Although they refer to interactional contexts as defined by the ACH and predict dual-language and dense CS contexts to involve high language entropy, Gullifer and Titone note that high language entropy does not automatically suggest CS behavior. Instead, CS is suggested as a strategy that allows bilinguals to reduce internal uncertainties in high entropy language environments. Consequently, a high language entropy environment may simply indicate a situation in which both languages are likely to occur but may not necessarily involve CS. For instance, an interactional context in which one bilingual code-switches while the other defaults to one language may still be regarded as a high-entropy situation, even though the second bilingual does not actively use both languages. From the reverse perspective, one individual is exposed exclusively to one language in the given situation, yet continues to engage in CS because they are aware of the bilingual abilities of their conversational partner, even though the environment does not explicitly demand it. Thus, in such a context, an important consideration is whether both interlocutors are mutually and actively engaging in CS. This mutual and active engagement could refine our understanding of a high entropy interactional context, where CS is possible and sometimes expected, but not necessarily the default mode of communication. Measures of language entropy, which capture the variability in language use within such interactions, could help identify instances where some bilinguals prefer to stick to one language even if their interlocutor switches codes, and vice versa. ACH suggests, for instance, that one speaker's refusal to engage in CS in a dense CS environment may be a potential source of an interactional cost. Understanding individual tendencies toward different language states in these contexts, resulting in varying degrees of exposure to or engagement in CS, can prevent the oversimplification of all bilinguals from high entropy "dense CS" contexts as a single group (see discussion on ACH). Future research could explore the interplay between language entropy and interlocutor effects through bilingual interaction patterns in different social contexts. Conversational analysis or network-based approaches could offer valuable insights into how bilinguals adjust their switching strategies based on interlocutor characteristics, such as language proficiency and perceived CS behavior.

The DMC framework provides a robust lens to understand how proactive and reactive control interact in varying language entropy environments. In the DMC, low expectancy of an event would result in the recruitment of reactive control, whereas high expectancy would lead to the mobilization of a proactive control strategy. Drawing upon this premise, an individual in a low-entropy environment—characterized by a predominant use of one language with minimal need for switching—is more likely to rely on reactive control strategies to manage the rare, unanticipated use of the non-target language. In such contexts, the lower expectancy for situations requiring the use of the non-target language reduces the necessity for continuous goal maintenance and proactive language preparation.

In contrast, as language entropy increases, the need to manage competing linguistic demands grows. High-entropy environments, where multiple languages are used in a balanced and frequent manner, demand proactive control to maintain readiness for the potential use of either language. This anticipatory mechanism enables bilinguals to flexibly and efficiently switch between languages as needed, ensuring seamless communication. This is reflected in findings showing higher engagement of proactive control in individual with high language entropy on various tasks (Gullifer et al., 2018; Li et al., 2021; van den Berg et al., 2022). However, even in high-entropy contexts, not all language switches can be fully anticipated. Reactive control remains crucial for resolving interference or addressing unexpected linguistic demands that arise spontaneously during interactions.

The connection between DMC and language entropy lies in this dynamic interplay between proactive and reactive control. High-entropy contexts encourage greater reliance on proactive control to prepare for frequent and fluid language transitions, while reactive control is deployed to handle unanticipated challenges. Future research could explore this interplay by investigating how bilinguals adapt their control strategies based on the level of language entropy in their daily interactions, using both naturalistic and experimental approaches, such as conversational analysis and language-switching paradigms.

Each framework we have presented provides unique insights, and understanding where they overlap or diverge can guide experimental designs and theoretical advancements (see Table 2 for a summary). For example, the ACH predicts that dense CS contexts reduce the need for interference suppression while emphasizing opportunistic planning, as the cooperative activation of both languages minimizes competition. In contrast, the DMC framework suggests that dense CS contexts involve a dynamic balance between proactive and reactive control:

TABLE 2 A brief summary of each framework highlighting key principles, unique contributions, testable predictions, and common themes with other frameworks.

Frameworks	Key principles	Unique contributions	Testable predictions	Common themes
Adaptive Control Hypothesis (ACH)	Interactional contexts modulate cognitive control processes.	Identifies 8 control processes involved in different interactional contexts.	Dual-language contexts enhance task-switching efficiency.	Interactional contexts influence cognitive control.
(Extended) Control Process Model (CPM)	Interactional contexts modulate cognitive control processes through CS types.	Introduces different control mechanisms for different CS types.	Dense CS contexts favor cooperative control.	Interactional contexts shape control mechanisms.
Dual Mechanisms of Control (DMC)	Proactive vs. reactive control modes.	Highlights individual and task-dependent variability of control modes.	Dense CS contexts train proactive control.	Context influences mode of cognitive control.
Language Entropy Approach	High contextual uncertainty necessitates adaptive control.	Introduces language entropy as a probabilistic measure of language use.	High-entropy contexts lead to smaller switch costs.	Language entropy influences cognitive control.

proactive monitoring anticipates upcoming switches, while reactive mechanisms resolve interference when it arises. These differing predictions could be tested through a combination of Stroop tasks (to measure interference suppression) and AX-CPT tasks (to differentiate between proactive and reactive control). Specifically, bilinguals from dense CS contexts might show reduced Stroop interference but excel in proactive control as measured by AX-CPT reaction times, aligning with DMC predictions. Alternatively, if opportunistic planning predominates in dense CS contexts as per the ACH, these individuals might demonstrate weaker reactive control but flexibility in switching tasks that allow linguistic freedom.

The Language Entropy Approach adds another layer by emphasizing the uncertainty inherent in high-entropy contexts, where both languages are equally likely to be used. It predicts that bilinguals in high-entropy contexts rely heavily on proactive control strategies, leading to smaller switch costs and enhanced task-switching efficiency. This hypothesis could be tested using language-switching paradigms to measure switch costs and task-switching experiments that assess the efficiency of proactive control. For instance, individuals from high-entropy environments could demonstrate reduced switch costs and better goal maintenance in tasks with predictable switching patterns compared to individuals from low-entropy contexts.

Another divergence lies in how frameworks conceptualize the role of matrix languages in CS. According to the ACH, insertion involves a clear matrix language, requiring strong interference suppression mechanisms to maintain its dominance while integrating elements from the embedded language. In contrast, alternation does not have a matrix language governing the sentence as a whole, instead involving larger chunks of speech from two languages with minimal interference suppression. The (Extended) CPM further refines this distinction by introducing competitive and cooperative control. Alternation may involve competitive control when it occurs between inter-clausal structures but cooperative control when it is intra-clausal, depending on the level of linguistic integration. Experimental tasks that manipulate insertion and alternation contexts could explore these differences. For example, EEG or neuroimaging studies could measure neural correlates of competitive vs. cooperative control during insertion and alternation tasks, while reaction time experiments could assess the cognitive load associated with maintaining a matrix language.

The DMC framework also offers testable hypotheses about how different interactional contexts shape the balance between proactive and reactive control. It predicts that bilinguals in single-language contexts will rely on reactive control given the lower expectation for switching, while those in dual-language contexts will be more likely to favor proactive control due to the high demand for goal maintenance. However, the preference for control mode in this context may be modulated by individual differences the efficacy of active goal maintenance. Dense CS speakers on the other hand are expected to demonstrate flexibility, dynamically switching between proactive and reactive modes as needed. This flexibility could be tested using goal maintenance tasks, such as the Flanker task (which emphasizes proactive control), and interference resolution tasks, such as the Stroop task (which emphasizes reactive control). Comparing bilinguals across single-, dual-, and dense CS contexts would provide valuable insights into how these contexts shape cognitive control strategies.

Finally, understanding the similarities and differences between these frameworks offers opportunities to bridge theoretical gaps. While the ACH, CPM, and DMC converge on the idea that interactional contexts influence cognitive control, they diverge in their predictions about the balance of proactive and reactive control in dense CS contexts, the role of matrix languages, and the specific mechanisms underlying language switching. For example, the ACH emphasizes opportunistic planning in dense CS contexts, the CPM focuses on the cooperative control required for intra-clausal alternation, and the DMC predicts a dynamic interplay between control modes. The Language Entropy Approach provides a broader perspective, framing bilingual language use as a spectrum and proposing that high-entropy contexts promote reliance on proactive control mechanisms. By integrating these frameworks, researchers could design studies that test not only the unique predictions of each model but also the conditions under which they converge or diverge. For example, experiments could manipulate linguistic entropy while varying task demands to assess whether proactive control is consistently favored across high-entropy contexts or whether certain tasks elicit a stronger reliance on reactive control. Similarly, the relationship between matrix language dominance and control processes could be explored by comparing intra- and inter-clausal alternations in dense CS contexts.

4 Conclusion

With this review, we presented a comparative, critical review of four frameworks of cognitive control implicated in CS. Among these, the Adaptive Control Hypothesis (ACH) and the Extended Control Process Model (CPM) have emerged in the past decade as particularly prominent and influential frameworks, serving as foundational pillars extensively tested in research on the intersection of cognitive control and CS. The Dual Mechanisms of Control (DMC), despite not being inherently focused on bilingual language use or CS, has been tested extensively within this domain and has consistently yielded results that largely align with the ACH and CPM. Finally, the language entropy approach presents a new perspective on bilingual language use. While acknowledging the influence of fluctuating language demands, aligning with the ACH and CPM, it conceptualizes language use as a spectrum from monolingual to multilingual, thus challenging the categorical notion of bilingualism. The language entropy approach appears to be compatible with the DMC framework as evidenced by empirical findings.

While the potential for an integrated comprehensive framework of cognitive control in CS is evident from our comparative review, it is crucial to acknowledge the limitations inherent in each framework, as pointed out in our discussion. Ambiguous terminology, methodological inconsistencies, and oversimplifications of complex cognitive processes hinder the possibility of seamless integration. Most significantly, interactional contexts play a critical role in nearly all studies guided by the reviewed frameworks, yet there is often ambiguity regarding whether these contexts refer to habitual contexts or the current context in experimental situations. This ambiguity leads to inconsistencies in research, blurring, for instance, the distinction between CS as stable traits of individuals and CS as temporary, context-dependent states. As a consequence, results from studies that approach CS as a trait may be conflated with studies of CS as a state. Moreover, the confusion in terminology, such as the usage of the term dense CS interchangeably with congruent lexicalization, poses challenges in categorizing CS types and interactional contexts accurately.

The measurement of CS and cognitive control is a critical aspect of understanding their relationship. A variety of methods have been used, each with distinct strengths and limitations. Self-report questionnaires, such as those by Rodriguez-Fornells et al. (2012), provide insights into language behavior but may suffer from limitations, as these rely on bilinguals' assumed inherent awareness of the frequency, intentionality, and patterns of CS. Individuals may not always accurately recall or be aware of their switching patterns, especially when distinguishing between inadvertent and intentional switches. More recently, tools like Olson (2022) questionnaire offer detailed insights by categorizing different types of CS (e.g., insertion, alternation, congruent lexicalization), providing a more comprehensive view of bilingual behavior. Experimental tasks, such as the code-switching frequency task (Hofweber et al., 2020), quantify CS behavior under controlled conditions, while language-switching paradigms, which prompt participants to switch languages on a cue, focus on the cognitive processes underlying intentional language switching and may fail to reflect real-life CS behavior. These approaches differ in their focus and may yield divergent results depending on whether they assess habitual behavior, task-induced switching, or underlying cognitive control mechanisms (for a review, see Rayo et al., 2024). These considerable differences in methodology not only complicates cross-study comparisons but also challenges our ability to fully understand the contributions and limitations of the theoretical frameworks themselves. Future research would benefit from integrating these methods to triangulate findings and better capture the complexity of CS behavior and its interplay with cognitive control. Furthermore, in studying the relationship between CS and cognitive control, as well as for a comprehensive framework, it is crucial to make a clear distinction between the production and processing of CS. Experimentally induced comprehension tasks involving CS cannot be assumed to reflect the production of CS, due not only to differences in the underlying processes of comprehension and production, but also the false assumption that a bilingual's passive exposure to CS should parallel their active use of it (cf. Cedden et al., 2024).

Finally, the role of data cleaning procedures in studying cognitive control warrants further attention. Different approaches to handling outliers, missing data, or preprocessing behavioral and neuroimaging data can introduce variability in findings. For instance, the choice of thresholds for reaction times or error rates, and whether trials with extreme values are excluded or retained, can significantly influence task performance measures and their interpretation. This variability underscores the need for standardized data cleaning protocols or, at the very least, transparent reporting of the methods employed. Future research should aim to investigate how specific data cleaning decisions impact conclusions drawn about cognitive control processes, especially in bilingualism research, where interactional contexts and code-switching behaviors are already sources of variability.

To overcome these challenges and move toward a more robust framework of cognitive control in CS, it is imperative to address and eliminate these limitations. Clear and standardized terminology, methodological rigor, and consideration of transience of CS behavior beyond individual differences are essential steps in this process. By doing so, we can ensure that future research in bilingualism yields more reliable and valid results, ultimately advancing our understanding of the cognitive control processes underlying bilingual language use and CS behavior.

Author contributions

BÖ: Conceptualization, Writing – original draft, Writing – review & editing. GC: Conceptualization, Supervision, Writing – review & editing. CS: Conceptualization, Funding acquisition, Supervision, Writing – review & editing. PM: Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Appel, R., and Muysken, P. (1987). *Language Contact and Bilingualism*. London: Edward Arnold.

Beatty-Martínez, A. L., Navarro-Torres, C. A., Dussias, P. E., Bajo, M. T., Guzzardo Tamargo, R. E., and Kroll, J. F. (2020). Interactional context mediates the consequences of bilingualism for language and cognition. *J. Exp. Psychol. Learn. Mem. Cogn*. 46, 1022–1047. doi: 10.1037/xlm0000770

Beatty-Martínez, A. L., Valdés Kroff, J. R., and Dussias, P. E. (2018). From the field to the lab: a converging methods approach to the study of codeswitching. *Languages* 3:19. doi: 10.3390/languages3020019

Braver, T. S. (2012). The variable nature of cognitive control: a dual mechanisms framework. *Trends Cogn. Sci*. 16, 106–113. doi: 10.1016/j.tics.2011.12.010

Cedden, G., Meyer, P., Özkara, B., and von Stutterheim, C. (2024). The "code-switching issue": transition from (socio)linguistic to cognitive research. *Biling. Lang. Cogn*. 1—14. doi: 10.1017/S1366728924000737

Cohen, J. D. (2017). "Cognitive control: core constructs and current considerations," in *The Wiley Handbook of Cognitive Control,* ed. T. Egner (Chichester; West Sussex: John Wiley & Sons), 3–28.

Gosselin, L., and Sabourin, L. (2023). Language athletes: dual-language code-switchers exhibit inhibitory control advantages. *Front. Psychol*. 14:1150159. doi: 10.3389/fpsyg.2023.1150159

Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Biling. Lang. Cogn*. 1, 67–81. doi: 10.1017/S1366728998000133

Green, D. W. (2018). Language control and code-switching. *Languages* 3:8. doi: 10.3390/languages3020008

Green, D. W., and Abutalebi, J. (2013). Language control in bilinguals: the adaptive control hypothesis. *J. Cogn. Psychol*. 25, 515–530. doi: 10.1080/20445911.2013.796377

Green, D. W., and Wei, L. (2014). A control process model of code-switching. *Lang. Cogn. Neurosci*. 29, 499–511. doi: 10.1080/23273798.2014.882515

Gullifer, J. W., Chai, X. J., Whitford, V., Pivneva, I., Baum, S., Klein, D., et al. (2018). Bilingual experience and resting-state brain connectivity: impacts of L2 age of acquisition and social diversity of language use on control networks. *Neuropsychologia* 117, 123–134. doi: 10.1016/j.neuropsychologia.2018.04.037

Gullifer, J. W., Kousaie, S., Gilbert, A. C., Grant, A., Giroud, N., Coulter, K., et al. (2021) Bilingual language experience as a multidimensional spectrum: associations with objective and subjective language proficiency. *Appl. Psycholinguistics*. 42, 245–278. doi: 10.1017/S0142716420000521

Gullifer, J. W., and Titone, D. (2019). Characterizing the social diversity of bilingualism using language entropy. *Bilingual. Lang. Cogn*. 23, 283–294. doi: 10.1017/S1366728919000026

Gullifer, J. W., and Titone, D. (2021). Bilingualism: a neurocognitive exercise in managing uncertainty. *Neurobiol. Lang*. 2, 464–486. doi: 10.1162/nol_a_00044

Han, X., Li, W., and Filippi, R. (2022a). Modulating effects of interactional contexts on bilinguals' cognitive control: evidence for the adaptive control hypothesis. *Int. J. Biling*. 27, 548–568. doi: 10.1177/13670069221102011

Han, X., Li, W., and Filippi, R. (2022b). The effects of habitual code-switching in bilingual language production on cognitive control. *Biling. Lang. Cogn*. 25, 869–889. doi: 10.1017/S1366728922000244

Hartanto, A., and Yang, H. (2016). Disparate bilingual experiences modulate task-switching advantages: a diffusion-model analysis of the effects of interactional context on switch costs. *Cognition* 150, 10–19. doi: 10.1016/j.cognition.2016.01.016

Hartanto, A., and Yang, H. (2020). The role of bilingual interactional contexts in predicting interindividual variability in executive functions: a latent variable analysis. *J. Exp. Psychol. Gen*. 149, 609–633. doi: 10.1037/xge0000672

Hofweber, J., Marinis, T., and Treffers-Daller, J. (2020). How different code-switching types modulate bilinguals' executive functions: a dual control mode perspective. *Biling. Lang. Cogn*. 23, 909–925. doi: 10.1017/S1366728919000804

Jiang, S., Ma, L., and Chen, B. (2023). Dynamic engagement of cognitive control in intra-sentential code-switching during comprehension. *Biling. Lang. Cogn*. 26, 62–77. doi: 10.1017/S1366728922000323

Kałamała, P., Szewczyk, J., Chuderski, A., Senderecka, M., and Wodniecka, Z. (2020). Patterns of bilingual language use and response inhibition: a test of the adaptive control hypothesis. *Cognition* 204:104373. doi: 10.1016/j.cognition.2020.104373

Kheder, S., and Kaan, E. (2021). Cognitive control in bilinguals: proficiency and code-switching both matter. *Cognition* 209:104575. doi: 10.1016/j.cognition.2020.104575

Lai, G., and O'Brien, B. A. (2020). Examining language switching and cognitive control through the adaptive control hypothesis. *Front. Psychol*. 11:1171. doi: 10.3389/fpsyg.2020.01171

Li, X., Ng, K. K., Wong, J. J. Y., Lee, J. W., Zhou, J. H., and Yow, W. Q. (2021). Bilingual language entropy influences executive functions through functional connectivity and signal variability. *Brain Lang*. 222:105026. doi: 10.1016/j.bandl.2021.105026

Morales, J., Gómez-Ariza, C. J., and Bajo, M. T. (2013). Dual mechanisms of cognitive control in bilinguals and monolinguals. *J. Cogn. Psychol*. 25, 531–546. doi: 10.1080/20445911.2013.807812

Morales, J., Yudes, C., Gómez-Ariza, C. J., and Bajo, M. T. (2015). Bilingualism modulates dual mechanisms of cognitive control: evidence from ERPs. *Neuropsychologia* 66, 157–169. doi: 10.1016/j.neuropsychologia.2014.11.014

Muysken, P. (2000). *Bilingual Speech: A Typology of Code-Mixing*. Cambridge: Cambridge University Press.

Muysken, P. (2013). Language contact outcomes as the result of bilingual optimization strategies. *Biling. Lang. Cogn*. 16, 709–730. doi: 10.1017/S1366728912000727

Ng, G., and Yang, H. (2022). Code-switching patterns differentially shape cognitive control: testing the predictions of the adaptive control hypothesis. *Biling. Lang. Cogn*. 25, 521–535. doi: 10.1017/S1366728921000754

Olson, D. J. (2022). The Bilingual Code-Switching Profile (BCSP): assessing the reliability and validity of the BCSP questionnaire. *Linguist. Approach. Bilingual*. 14, 400–433. doi: 10.1075/lab.21039.ols

Rayo, W., Barrita, A. M., Cabrera Martinez, L., and Carbajal, I. (2024). The complexity in bilingual code-switching research: a systematic review. *Languages* 9:217. doi: 10.3390/languages9060217

Rodriguez-Fornells, A., Kramer, U., Lorenzo-Seva, U., Festman, J., and Münte, T. F. (2012). Self-assessment of individual differences in language switching. *Front. Psychol.* 2:388. doi: 10.3389/fpsyg.2011.00388

Rosvold, H. E., Mirsky, A. F., Sarason, I., Bransome, E. D. Jr., and Beck, L. H. (1956). A continuous performance test of brain damage. *J. Consult. Psychol.* 20, 343–350. doi: 10.1037/h0043220

Struys, E., Woumans, E., Nour, S., Kepinska, O., and van den Noort, M. (2019). A domain-general monitoring account of language switching in recognition tasks: evidence for adaptive control. *Biling. Lang. Cogn.* 22, 606–623. doi: 10.1017/S1366728918000342

Treffers-Daller, J. (2020). "Turkish-German code-switching patterns revisited: what naturalistic data can(not) tell us," in *Advances in Contact Linguistics. In honour of Pieter Muysken*, eds. N. Smith, T. Veenstra, and E. O. Aboh (Amsterdam/Philadelphia: John Benjamins Publishing Company), 237–260.

van den Berg, F., Brouwer, J., Tienkamp, T. B., Verhagen, J., and Keijzer, M. (2022). Language entropy relates to behavioral and pupil indices of executive control in young adult bilinguals. *Front. Psychol.* 13:864763. doi: 10.3389/fpsyg.2022.864763

Wagner, D., Bekas, K., and Bialystok, E. (2023). Does language entropy shape cognitive performance? A tale of two cities. *Bilingual. Lang. Cogn.* 26, 998–1008. doi: 10.1017/S1366728923000202