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The impact of emotional states on bilingual language control in cued and voluntary switching contexts

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ABSTRACT

This study investigated bilingual language control in emotional contexts. We assessed the language switching and mixing performance of two groups of Chinese-English bilinguals in picture naming under neutral, negative, and positive emotional states. One group switched languages voluntarily while another matched group switched languages according to external cues. We found that negative state impaired proactive control, whereas positive state seemed to improve proactive control. Importantly, the detrimental effects of negative state could be proportional to the cognitive demands imposed by the naming context. However, negative states disrupted proactive control in voluntary but not cued naming, where the proactive control demands were comparable. This finding suggests that the control system selectively compensates for the emotional disruption of control in a cued-naming context requiring strict control but not in a voluntary-naming context preferring less strict control. Accordingly, we tentatively proposed a theoretical account of the adaptive control mechanism in emotional contexts. These findings would extend the Adaptive Control Hypothesis to more naturalistic settings.

Introduction

A bilingual's two languages may always be active, even when only one is required (Thierry & Wu, 2007). This process might be expected to produce frequent language errors, but unintended cross-language intrusions are rare in spontaneous speech and the laboratory (Gollan et al., 2011). Bilinguals must, therefore, benefit from a control mechanism that allows them to select which language to use at a given moment and in a given context (Abutalebi et al., 2008).

There is growing evidence that the control processes are not fixed but differ depending on context (Jiang et al., 2023, 2024). In line with the influential Adaptive Control Hypothesis (ACH, Green & Abutalebi, 2013), much research has found that the language control mechanism varies as a function of the social context of the communication (i.e., interactional context) (Blanco-Elorrieta & Pylkkänen, 2017; Rafeekh & Mishra, 2021). Some studies, for example, have revealed that stricter language control is used when switching in response to external cues (e.g., the monolingual interlocutor) than when switching language voluntarily (e.g., when surrounded by other bilinguals speaking the same languages) (de Bruin et al., 2020; Jevtović et al., 2020).

In this study, we tried to broaden the notion of context by examining whether and how bilinguals' language control system differs depending on their emotional states. In life, bilingual language production often occurs in a state of heightened emotion (Dewaele & Costa, 2013; MacIntyre & Gardner, 1991a; Pavlenko, 2004). For example, language learners often experience negative affect (e.g., fear and anxiety) when they have to speak in a second language (L2) (Cohen & Norst, 1989). Bilinguals may feel stressed when forced to switch languages (Smith et al., 2020). However, there is a lack of direct and reliable empirical evidence regarding whether and how emotional states affect bilingual language control.

Furthermore, according to the ACH, the control system itself adapts to the demands placed on them by the interactional context. This study further explored how this adaptive control mechanism proposed by the ACH works in emotional contexts. One possibility is that it functions as initially proposed in the ACH. Here, we propose another possibility: the control system adaptively triggers compensatory control processes in the face of emotional disruptions according to the communicative/task goals in the interactional contexts. The two possibilities, in turn, would result in different patterns of the interaction between interactional contexts and emotional states in modulating control processes during bilingual language production. Thus, to adjudicate between the two possibilities, we investigated the interaction of the effects of emotional states with (cued versus voluntary) switching contexts. The findings

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would extend the predictions of ACH by incorporating within-individual variation in emotional states, and thus further unravel complex bilingual language control mechanisms in the real world where diverse types of contexts (e.g., social and personal contexts) appear to affect language processing within the same time frame (Hasson et al., 2018).

Emotional states and language control

Substantial experimental evidence indicates that emotional states influence various cognitive processes, including cognitive control (Figueira et al., 2017). At the same time, it has been repeatedly shown that cognitive control is involved in bilingual language production (Jylkkä et al., 2018; Liu et al., 2016). Thus, bilingual language control can differ depending on emotional states. However, the available supportive evidence is mainly indirect and far from conclusive.

Evidence comes, firstly, from the negative association between foreign language anxiety and L2 speech production performance (Hewitt & Stephenson, 2012; MacIntyre & Gardner, 1989, 1991b; Wilson, 2006). Specifically, in L2 oral examinations, individuals with high foreign language anxiety produce more errors, including first language (L1) lexical intrusions, a form of language control failure (Hewitt & Stephenson, 2012; Wilson, 2006). Moreover, they have deficits in lexical access (i.e., generate fewer items) when tested in L2 verbal fluency tasks (MacIntyre & Gardner, 1989, 1991b), which is probably due to language control deficiency (i.e., high interference from the non-target language) (Bialystok et al., 2008; Ivanova et al., 2016; Sandoval et al., 2010). It should be noted, however, that mainly weak correlations between foreign language anxiety and L2 speech production performance were observed ($|r|$ range = 0.34–0.40). Moreover, these findings do not necessarily require a control deficiency account to explain them. For example, the inferior performance in L2 verbal fluency tasks within anxious individuals can be explained in terms of vocabulary deficit resulting from the impairment of anxiety on vocabulary learning (MacIntyre & Gardner, 1994).

Further evidence supporting the effect of heightened emotional states derives from the findings that bilinguals are more likely to switch between languages when talking about past emotional events or expressing emotion (e.g., when swearing or reprimanding) (Buxbaum, 1949; Dewaele, 2010, 2015; Dewaele & Costa, 2013; Greenson, 1950; Krapf, 1955; Movahedi, 1996; Pavlenko, 2004, 2005; Resnik, 2018; Rolland et al., 2017; Rozensky & Gomez, 1983; Santiago-Rivera et al., 2009). One explanation is that the heightened emotional state the individuals experienced when coding and expressing emotions interferes with strict inhibitory control of the non-target language, thus leading to unintended language switching (Dewaele, 2010). Evidence of the relation between language switching and heightened emotional states, nevertheless, is primarily restricted to clinical case studies of bilingual patients (Buxbaum, 1949; Greenson, 1950; Krapf, 1955; Movahedi, 1996; Rozensky & Gomez, 1983) and self-report studies (Dewaele, 2010, 2015; Pavlenko, 2004, 2005; Resnik, 2018), leaving open both the generalizability and specificity of this link.

Williams et al. (2019) examined the associations between emotional states and code-switching frequency by observing 34 pairs of Chinese-American children and parents from bilingual immigrant families during a 5-minute emotion-inducing puzzle box task. The frequency of parents' code-switching and the valence and intensity of their facial emotion behavior were coded at each 5-s interval. The results revealed that more intense negative facial emotion behavior was associated with increased code-switching at the subsequent 5-s epoch (i.e., parents switched more frequently *after* showing more negative facial emotion). The association between positive facial emotion and code-switching frequency at the subsequent 5-s epoch did not reach significance. However, more intense positive facial emotion predicted decreased concurrent code-switching frequency (i.e., parents switched less often *when* expressing more positive facial emotion). Williams et al. (2019) interpreted this finding by proposing that a negative emotional state temporarily disrupts cognitive control engaged in language control, thereby freely permitting entry of items from both languages into speech output and inducing more frequent code-switching. On the other hand, a positive emotional state facilitates cognitive control involved in language control, thus resulting in less frequent code-switching.

Williams et al. (2019) provided the first empirical evidence for the association between emotional states and language switching. However, using observational measures, they did not manipulate bilingual speakers' emotional states and thus might not adequately reveal the causal connection between emotional states and language switches. Moreover, the switch rate may not be a reliable index for language control efficiency. Put concretely, the relationship between switch rate and language control efficiency may be modulated by the (unintended versus voluntary) types of switching. On the one hand, cross-language intrusions have been found to increase with declines in cognitive control (Gollan et al., 2011). Increases in voluntary language switching, on the other hand, have been reported to be linked to better efficiency in language control, though this link is not consistently observed (de Bruin et al., 2020; Gollan & Ferreira, 2009).

Taken together, the current study investigated the impacts of experimentally-induced emotional states on three prominent markers of top-down language control – namely, switching cost, mixing cost, and the reversed language dominance effect (as discussed below), in order to offer more compelling evidence for whether and how bilingual language control processes vary depending on emotional states.

Adaptive control mechanism in emotional contexts

In the following section, we begin by describing the ACH and different switching contexts. Next, we propose two possibilities for how the adaptive control mechanism operates in emotional contexts and how switching contexts and emotional states interact in modulating control processes.

In the ACH, Green and Abutalebi (2013) distinguish three interactional contexts (single language, dual language, and dense code-switching). In the single-language context, languages are used separately in distinct environments (e.g., one language at work and the other at home), and language switching rarely occurs. In the dual-language context, both languages are used in the same environment, but different languages are used with different addressees (e.g., two languages are used at work but with different monolingual colleagues with different language backgrounds), and bilinguals may switch languages in conversational turns with different addressees. The interference must be resolved in these two contexts to avoid cross-language intrusion errors. Consequently, a set of top-down control processes are implemented in the single-language context to ensure efficient suppression of the nontarget language over extended periods of time. In the dual-language context, a wider range of cognitive processes are triggered as a consequence of the increased demands for interference inhibition, language switching, and constant monitoring of the appropriate language. Finally, in the dense code-switching context, bilinguals share the same languages and may switch languages within a single conversational turn for no apparent external reasons. Bilinguals may use an opportunistic planning approach to use the words and constructions that are most readily available regardless of their language membership. This context is the least demanding, as it comes with limited needs for additional control processes.

The bilingual language control mechanism is most often tested by a cued language switching task, which requires bilinguals to name pictures or digits in response to a cue indicating which language to use (Costa & Santesteban, 2004; Meuter & Allport, 1999). Some recent studies (de Bruin et al., 2018; de Bruin & Xu, 2022; Zhu et al., 2022), however, investigated voluntary language switching where participants named pictures/digits in their language of choice. While the cued language switching is similar to a dual-language context, the voluntary language switching is comparable to a dense code-switching context

(Blanco-Elorrieta & Pylkkänen, 2018; de Bruin et al., 2018, 2020; Jevtović et al., 2020). In line with the ACH, voluntary language switching has been observed to be at least partly driven by bottom-up processes related to lexical access in the case of opportunistic planning (Blanco-Elorrieta & Pylkkänen, 2017; Gollan et al., 2014; Gollan & Ferreira, 2009; Jevtović et al., 2020; Kleinman & Gollan, 2016; Zhu et al., 2022). Moreover, studies comparing different switching contexts have observed that more (top-down) language control is needed during cued than voluntary context (Blanco-Elorrieta & Pylkkänen, 2017; de Bruin et al., 2018, 2020; de Bruin & Xu, 2022; Gollan et al., 2014; Gollan & Ferreira, 2009; Jevtović et al., 2020; Zhu et al., 2022), which aligns with the proposal in the ACH that dual-language context imposes more demands on control processes than dense code-switching context (de Bruin & Xu, 2022). Furthermore, it has been observed that relative to having to stay in one language (most comparable to the single-language context in the ACH), forced mixing is more costly while freely mixing two languages is less effortful (de Bruin et al., 2018; de Bruin & Xu, 2022). This line of evidence is in accord with the proposal in the ACH that single-language context involves lower levels of control than dual-language context, but triggers higher levels of control than dense code-switching context.

It should be noted that the studies discussed above mainly tested habitual code-switchers (Blanco-Elorrieta & Pylkkänen, 2017; de Bruin et al., 2018, 2020; de Bruin & Xu, 2022; Jevtović et al., 2020) who may find it relatively cognitive effortless to process the code-switches that are congruent with their usual mode of language use (Green & Abutalebi, 2013). It remains unclear whether a similar pattern of results could emerge for non-habitual code-switchers, for whom switching may be unnatural and effortful, and voluntary switching may require some higher order decision regarding what language to use and when to switch. However, several studies (Jiao et al., 2022; Liu et al., 2021) testing Chinese-English bilinguals from a non-habitual codeswitching community (i.e., universities in Mainland China) have reported (some) benefits in voluntary over cued language switching, thus providing preliminary evidence for the ACH in the case of non-habitual code-switchers (though for this bilingual sample, voluntary switching might engage somewhat different mechanisms, such as executive decision, than those involved in dense code-switching).

Given the differences between cued and voluntary contexts discussed above, two possibilities can be raised for how the adaptive control mechanism operates in emotional contexts, which would be reflected in the interaction between switching contexts and emotional states. An intuitive possibility, the cognitive effort account, is that the control system functions as initially proposed in the ACH (Green & Abutalebi, 2013); thus, voluntary language switching could be less cognitively demanding than cued language switching (de Bruin et al., 2018; Gollan et al., 2014; Jevtović et al., 2020). In this case, emotional effects should be less robust in voluntary than cued switching because the impact of emotional states has been widely observed to be greatest with relatively difficult and demanding tasks (Egidi & Gerrig, 2009; Forgas, 1995; Seibert & Ellis, 1991).

Here, we propose an alternative and more intriguing possibility, namely, the adaptive compensatory control account: the control system may selectively compensate for temporary language control failures when strict language control is required (e.g., during cued switching) but not when less strict control is preferred (e.g., during voluntary switching). On this view, cued switching would be more resistant to the (detrimental) emotional effects than voluntary switching. Specifically, prior research indicates that deviations from required performance (e.g., errors or delayed responses) trigger compensatory adjustments in control processes, which bring behavior more in line with task goals (Botvinick et al., 2004; Green & Abutalebi, 2013). For instance, in the flanker task, the difference between conflicting and non-conflicting trials is reduced after a conflicting trial (Botvinick et al., 2004). Hence, additional control processes may be triggered to compensate for the detrimental effects of (negative) emotional states (if any) when top-down language control failures, such as cross-language intrusions, cause deviation from the task goal.

As discussed above, interactional contexts have been proposed to differ in terms of communicative/task goal (Green & Abutalebi, 2013). Specifically, bilinguals in single- and dual-language contexts establish and maintain task goals such as speaking in one language rather than another and avoiding cross-language intrusions. On the contrary, bilinguals in a dense code-switching context aim to use both languages opportunistically, circumventing the need to strongly suppress non-target languages (Green & Abutalebi, 2013). Thus, increases in top-down language control failures under (negative) emotional states would deviate from the task goal in single- and dual-language contexts. In contrast, given the lack of negative consequences of selecting the "wrong" language (e.g., cross-language intrusions can be used opportunistically) in the dense code-switching context (Green & Abutalebi, 2013), top-down language control failures may not deviate from the task goal in this context. Consequently, compensatory adjustments in control processes would be triggered in single- and dual-language contexts but not in dense code-switching contexts. Accordingly, the detrimental effects of (negative) emotional states, if any, should be more robust in voluntary switching (comparable to a dense code-switching context) than cued switching (comparable to a dual-language context).

The present study

The present study aims to examine bilingual language control in emotional contexts. We focus on whether and how emotional states can modulate bilingual language control and how emotional states and switching contexts interact.

The experiment featured a mixed design with task group (voluntary vs. cued) as a between-group factor and emotion (neutral vs. negative vs. positive), trial type (switch trials in mixed-language conditions vs. nonswitch trials in mixed-language conditions vs. blocked trials), and language (L1 vs. L2 trials) as within-group factors. One group of Chinese-English bilinguals from a non-habitual codeswitching community completed a voluntary task where they named pictures in their language of choice, while another matched group performed a cued task where pictures had to be named in Chinese or English in response to a cue. The two tasks were matched for the average switch rate, which has been reported to affect control processes (Jylkkä et al., 2018) and thus may interfere with the influence of switching type. All participants were tested under negative, positive, and neutral states generated by a standard emotion-induction procedure involving music and guided rumination (Chepenik et al., 2007; Guo et al., 2020; Jefferies et al., 2008; Rowe et al., 2007; Spachtholz et al., 2014; van Steenbergen et al., 2010).

Three prominent markers of language control, namely, switching cost, mixing cost, and the reversed language dominance effect (RLDE), were used. The switching cost refers to poorer performance (e.g., slower response speed and reduced naming accuracy) on switch trials (a response in a different language than in the previous trial) than non-switch trials (a response in the same language as on the previous trial) (Green, 1998). The mixing cost refers to worse performance on non-switch trials in mixed language conditions than trials in blocked single-language conditions in which bilinguals must use one pre-specified language (Ma et al., 2016). Notably, switching into the dominant L1 often incurs a greater switching cost than switching into the nondominant L2 (Costa & Santesteban, 2004; Meuter & Allport, 1999), and the dominant L1 often incurs larger mixing costs than the nondominant L2 (Christoffels et al., 2007; Peeters & Dijkstra, 2018) (especially for unbalanced bilinguals). Typically, when both switching and mixing costs are measured, the asymmetry across languages is present in only one of them (Declerck, 2020). The RLDE refers to slower responses in the dominant L1 than in the nondominant L2 in the mixed language condition (Christoffels et al., 2007; Costa & Santesteban, 2004).

As for the effect of emotional states, based on previous research

(Dewaele, 2010; Williams et al., 2019), we hypothesized that negative states should disrupt language control, while positive states should boost the control system. Increased control efficiency would manifest as overall faster responses (Wu & Struys, 2021), smaller switching cost (de Bruin et al., 2018, 2020; Gollan & Ferreira, 2009; Weissberger et al., 2012), smaller switching cost asymmetry (Liu et al., 2016), smaller mixing cost (de Bruin et al., 2020; Weissberger et al., 2012) and larger RLDE (see Stasenko et al., 2021 for discussion of aging-related deficit in dominance reversal). Thus, we expected overall slower responses, a larger switching cost, switching cost asymmetry, mixing cost, and smaller RLDE under a negative than neutral state. By contrast, there should be overall faster responses, a smaller switching cost, switching cost asymmetry, mixing cost, and larger RLDE under a positive than neutral state. Whereas the switching cost and its asymmetry represent a reactive type of language control, the RLDE and the mixing cost have been associated with a more proactive type of control (for reviews of measures of reactive and proactive language control, see Bobb & Wodniecka, 2013; Declerck, 2020). Reactive language control resolves cross-language interference after it is detected; however, proactive language control anticipates and prevents potential interference before it occurs (Declerck, 2020). Reactive control is implemented at the local, trial-by-trial level, but proactive control is implemented at the global, non-trial-specific level (Ma et al., 2016). In addition, we used the switch rate as a supplementary index for language control in voluntary tasks. Following previous research (Williams et al., 2019), we expected more frequent switching under the negative than the neutral state but less frequent switching under the positive than the neutral state.

Two possibilities for how the adaptive control system operates in emotional contexts are considered: (1) it operates as initially proposed in the ACH (Cognitive effort account), or (2) it adaptively triggers the compensatory mobilization of top-down control according to the communicative goals in the interactional contexts (Adaptive compensatory control account). Concerning the interplay between switching contexts and emotional states, two different patterns can be expected based on the two accounts. According to the cognitive effort account, voluntary switching should reveal a less robust emotional effect than cued switching, regardless of whether the emotional effect is detrimental or facilitative. The adaptive compensatory control and the cognitive effort accounts contradict their predictions regarding whether the cued or voluntary switching context exhibits greater emotional disruption. Specifically, according to the adaptive compensatory control account, when the emotional effect is detrimental, a compensatory mobilization of top-down control should be triggered in cued switching, where a loss of strict control deviates from the task goal. However, it should not be triggered in voluntary switching, where a loss of strict control does not deviate from the goal-related requirement. Accordingly, relative to the voluntary switching context, cued switching should be more resistant to the detrimental effect of, for example, negative states.

Note that the present study is based on the assumption that voluntary switching is less costly than cued switching, even for non-habitual code-switchers. Accordingly, we expected to find faster responses, smaller switching costs, and mixing costs in voluntary than cued switching context (de Bruin et al., 2018, 2020; Jevtović et al., 2020; Jiao et al., 2022) at least in neutral state. However, given that the non-habitual code-switchers may find the voluntary switching unnatural and effortful, we expected smaller benefits in voluntary over cued language switching relative to those previously observed in habitual code-switchers (e.g., Jevtović et al., 2020).

Method

Participants

One hundred and twelve Chinese-English bilinguals from Beijing Normal University in China, with normal/corrected vision and no self-reported history of neurological/psychological impairments or psychoactive medication, participated for monetary compensation. All participants signed the written informed consent. Ethical approval was obtained from the Committee of Protection of Participants at Beijing Normal University. Fifty-seven bilinguals were invited to participate in the voluntary task. The final sample consisted of 54 participants (40 females) who chose no more than 65% of the time the preferred language (i.e., Chinese) in a screening test (the picture stimuli and procedure of which is similar to that of the voluntary task in the main experiment). Three months later, another 55 bilinguals (47 females) participated in the cued task.

Table 1 illustrates the characteristics of each final group of participants. Participants' linguistic background and language proficiency were mainly assessed using the Language History Questionnaire (LHQ, version 3) (Li et al., 2020). All participants were exposed to Chinese (L1) from birth and learned English (L2) in a classroom setting. They never lived or traveled abroad in English-speaking countries for over three months, with two exceptions in the cued task. Paired samples *t* tests revealed that participants in each group were dominant in their L1 in listening [voluntary task group: $t(53) = 13.14$, $p < 0.001$; cued task group: $t(54) = 11.85$, $p < 0.001$], speaking [voluntary task group: $t(53) = 12.78$, $p < 0.001$; cued task group: $t(54) = 11.93$, $p < 0.001$], reading [voluntary task group: $t(53) = 10.27$, $p < 0.001$; cued task group: $t(54) = 10.45$, $p < 0.001$], and writing [voluntary task group: $t(53) = 10.85$, $p < 0.001$; cued task group: $t(54) = 10.76$, $p < 0.001$] skills. Their average score on the Quick Placement Test (QPT, version 2) was equivalent to the B1 (i.e., lower intermediate) level in the Common European Framework of Reference (CEFR) based on the testing manual. Moreover, the relatively low overall total score on the Bilingual Switching Questionnaire (BSWQ) (Rodriguez-Fornells et al., 2012) indicated that these bilinguals seldom engaged in code-switching in their daily lives. Finally, a series of independent samples *t* tests confirmed that the two groups were closely matched on critical demographic characteristics.

Materials

Picture naming

Black-and-white line drawings from Snodgrass and Vanderwart (1980) were used for voluntary and cued picture naming. All names in Chinese were bisyllabic words, and all English were mono or bisyllabic words, ranging from 3 letters to 6 letters in length. Twenty-six Chinese-English bilinguals (24 females; average age: 24.3 years, $SD = 3.65$) whose English proficiency is close to participants in the formal experiment (i.e., both groups passed the College English Test Band 4, an official English test implemented by the Ministry of Education of China to measure Chinese non-English major college student's English proficiency in writing, listening, reading, and translating) rated their familiarity with the Chinese and English names on a 5-point scale (1 = *very unfamiliar*; 5 = *very familiar*).

A set of 16 (and eight filler) line drawings were selected for the formal experiment. Paired samples *t* tests showed that there was no significant difference between the familiarity for Chinese ($M = 4.91$, $SD = 0.06$) and English ($M = 4.92$, $SD = 0.06$) names of the 16 target stimuli, $t(15) = -0.70$, $p = 0.50$. In addition, the naming agreement (measured by the H statistic, referring to the number of different names speakers use to refer to a given object) in Chinese ($M = 0.64$, $SD = 0.54$, *range* = 0–1.58) and English ($M = 0.47$, $SD = 0.39$, *range* = 0–1.37) is not significantly different for the target stimuli, $t(15) = 1.28$, $p = 0.22$. Naming agreement data in Chinese and English were retrieved from Zhang and Yang (2003) and Snodgrass and Vanderwart (1980), respectively.

Additionally, a different set of 16 (and four filler) line drawings were selected for the screening test in the voluntary task. In this set of target stimuli, the difference between the familiarity with Chinese ($M = 4.80$, $SD = 0.14$) and English names ($M = 4.86$, $SD = 0.12$) and the difference between the naming agreement in Chinese ($M = 0.78$, $SD = 0.45$, *range*

Table 1
Characteristics of participants in voluntary and cued tasks.

	Voluntary task group		Cued task group		Comparison of two groups	
	M	*SD*	*M*	*SD*	*t*	*p*
Age (years)	23.04	2.55	22.60	1.72	−1.05	0.30
Years of English learning	15.35	3.08	15.55	2.90	0.34	0.74
Self-reported Chinese proficiency[a]						
Listening	6.09	0.85	5.80	0.89	−1.75	0.08
Speaking	5.63	1.10	5.58	0.98	−0.24	0.81
Reading	6.07	0.97	5.84	0.90	−1.33	0.19
Writing	5.54	1.09	5.36	0.99	−0.87	0.39
Self-reported English proficiency[a]						
Listening	4.00	0.99	3.71	1.18	−1.40	0.17
Speaking	3.48	0.88	3.51	1.18	0.14	0.89
Reading	4.65	0.93	4.55	0.88	−0.59	0.56
Writing	4.00	0.85	3.98	1.06	−0.10	0.92
Quick placement test (QPT)[b]	38.39	5.75	38.64	5.96	0.22	0.83
Bilingual Switching Questionnaire (BSWQ)[c]	32.89	5.35	31.44	4.47	−1.54	0.13
Foreign language classroom anxiety scales (FLCAS)[d]	100.26	23.85	100.05	22.95	−0.05	0.96

Note: [a] Ratings were on a scale from 1 (very poor) to 7 (excellent). [b] Quick Placement Test (QPT, version 2) was administered to obtain the objective indicator of English proficiency. The larger values on the scores indicate higher levels of English proficiency (total score: 60). [c] BSWQ is composed of 12 items measuring the frequency of switching behavior. Ratings ranged from 1 (never) to 5 (always). The larger values on the scores indicate more frequent switching (total score: 60). [d] Chinese version of the Foreign Language Classroom Anxiety Scale (FLCAS) (Horwitz et al., 1986; Shao et al., 2013) was administered to assess foreign language anxiety. The larger values on the scores indicate higher levels of anxiety (total score: 165). Scores above 132 signify high anxiety, scores between 99 and 132 denote a middle level of anxiety, and scores below 99 imply little or no anxiety.

= 0–1.48) and English ($M = 0.51$, SD = 0.49, *range* = 0–1.68) did not reach significance (all $|t|$s < 1.56, all *ps* > 0.14).

Emotion elicitation and assessment

Twenty-seven pieces of instrumental music (9 pieces per emotion condition; 22050 Hz, 16 bits; each lasting about 1 min) from the Chinese Affective Music System (CAMS, Li et al., 2012) were used for emotion elicitation. Musical pieces from the CAMS have been validated for successfully inducing target emotional states (Cheng et al., 2017).

One-way ANOVA was performed on the arousal and pleasure ratings extracted from Li et al. (2012). The results showed a significant main effect of emotion type for arousal [$F(2) = 86.92, p < 0.001$] and pleasure ratings [$F(2) = 161.50$, $p < 0.001$]. Tukey post-hoc analysis revealed that positive musical pieces (arousal: $M = 6.84$, $SD = 0.47$; pleasure: $M = 6.93$, $SD = 0.42$) were significantly higher than neutral musical pieces (arousal: $M = 4.58$, $SD = 0.57$; pleasure: $M = 4.91$, $SD = 0.39$) in arousal and pleasure ratings (*ps* < 0.001). Negative musical pieces (arousal: $M = 3.72$, $SD = 0.52$; pleasure: $M = 3.47$, $SD = 0.42$) were significantly lower than neutral musical pieces in arousal and pleasure ratings (arousal: $p < 0.01$; pleasure: $p < 0.001$). One-way ANOVA on lengths revealed non-significant differences across positive, negative, and neutral musical pieces, $F(2) = 0.93$, $p = 0.41$. The sound intensity of all musical pieces was matched using Adobe Audition CS6 software.

The induced emotional state was measured via a paper-and-pencil 9 × 9 Affect Grid (Russell et al., 1989), which assesses emotion on the dimensions of pleasure (1 = *extremely unpleasant feelings*; 9 = *extremely pleasant feelings*) and arousal (1 = *extreme sleepiness*; 9 = *extremely high arousal*).

Procedure

The task was presented using E-prime 2.0 (Psychology Software Tools, Inc., PA, USA). Responses were collected via a Serial Response Box (Psychology Software Tools, Inc., PA, USA) and recorded on a digital recorder. Before starting the formal experiment, participants completed the background questionnaires described above. To avoid errors due to not recognizing the pictures or using the wrong word, participants were familiarized with the 16 target and 8 filler picture stimuli and the corresponding names. Each participant then performed a short practice naming task involving the filler stimuli and including all three naming conditions (i.e., L1 blocked, L2 blocked, and mixed-language) as in the main experiment. The naming conditions, each composed of 8 trials, were presented in the same order as in the main task. Next, participants were instructed how to rate their emotional state with 9 × 9 Affect Grid (for examples of the instructions, see Jefferies et al., 2008; Russell et al., 1989). They were told to do this whenever a 9 × 9 Affect Grid appeared on the screen 24 times during the experimental session. After this instruction, participants were given earphones to wear for the duration of the experiment. Fig. 1 illustrates the schematic diagram of the main experimental procedure in each emotion condition.

Block and trial structures for picture naming in each emotion condition

In each emotion condition, voluntary and cued naming tasks consisted of one part in which all naming was done in one language (i.e., either L1 or L2) and another in which the languages were mixed. The single-language section was always administered first, followed by the mixed-language section (Gollan et al., 2014; Ma et al., 2016).

Single-language section. Each single-language section included two subsections. In each subsection, participants were asked to name all pictures in L1 or L2 only (i.e., pure L1 block and pure L2 block). The order of pure L1 block and pure L2 block was counterbalanced between participants. Within each single-language block, each picture was repeated twice (32 trials in each block), and one practice trial (filler picture) was followed by the experimental trials without a break. Experimental trials within blocks were pseudorandomized across participants, such that the same item (picture) never appeared consecutively. Instructions for all single-language blocks were presented on the screen in the language in which the pictures had to be named. Each trial started with a fixation cross for 750 ms. Then, the pictures to be named were presented for 2000 ms or until response. Participants were asked to name the pictures aloud as fast and correctly as possible, and their responses were recorded. Lastly, after a 1000 ms blank screen, the next trial began.

Mixed-language section. Participants in the voluntary group were free to choose which language to name each picture in the mixed-language section. The instructions were as follows: "In the following part, you can name the pictures in Chinese or English. You are free to switch between languages whenever you want. Try to use the word that comes to mind first, but do not use the same language throughout the whole task" (de Bruin et al., 2018). The trial structure was similar to the one used in the single-language section.

Participants in the cued group were required to name the picture in

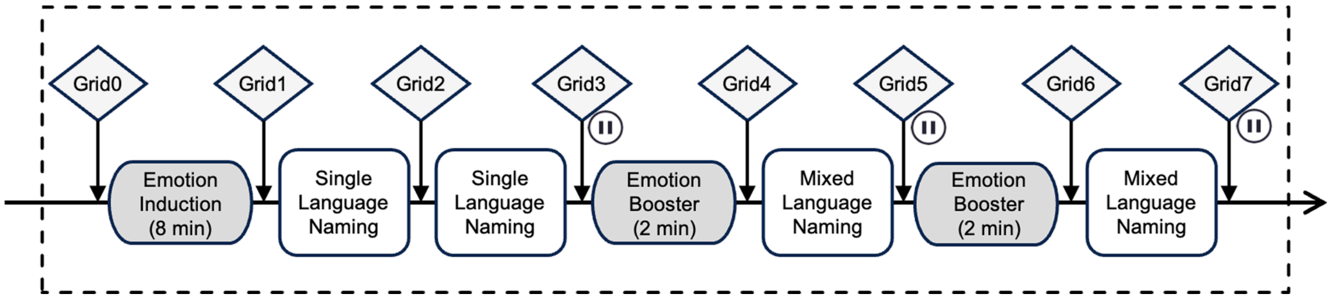

Fig. 1. Schematic diagram of the procedure in each emotion condition. Participants were given a break after the two single-language blocks and each mixed-language block. Grid = 9 × 9 Affect Grid.

the language corresponding to the color square presented prior to the picture in the mixed-language section. The trial structure was similar to the one used in the single-language condition. However, each trial started with a language cue (color square) for 250 ms, followed by a 500 ms blank screen. Then, the pictures to be named were presented. The color-cue (blue or red) to language (Chinese or English) assignment was constant throughout the mixed section for each bilingual but was counterbalanced between participants.

For both voluntary and cued groups, the instructions in the mixed section were provided on the screen in both Chinese and English. The order in which the languages appeared on the screen (top or bottom half) was counterbalanced across participants. Two trial type conditions were included in the mixed section – switch trials (in which the chosen language differed from the preceding trial) and nonswitch trials (in which the chosen language was the same as in the preceding trial).

The mixed section consisted of 128 trials in total, distributed across two subsections (64 trials per subsection). Each picture was repeated eight times (four times per subsection). For the voluntary task group, experimental trials within the mixed section were pseudorandomized across participants, such that the same item never appeared consecutively. For the cued task group, each mixed subsection began with a practice picture, which set the task for the first experimental trial of the subsections (i.e., as a switch or a nonswitch trial). Language switches were cued on 32 of the 128 trials (16 of the 64 trials per language) in the cued mixed section. Each item appeared once in a Chinese-switch trial, once in an English-switch trial, three times in Chinese-nonswitch trials, and three times in English-nonswitch trials. This 25% switch rate matches the average switch rate reported for voluntary switching (as discussed below). For the cued task group, nine lists with nine different pseudorandom orders were created in each emotion condition following three constraints: (1) the same item never appeared consecutively; (2) the two switch trials and six nonswitch trials each item appeared were equally distributed in the two subsections – that is, within each subsection, each item appeared once in a switch trial and three times in nonswitch trials[1]; (3) the 4 Chinese trials and 4 English trials each item appeared in were equally distributed in the two subsections – that is, within each subsection, each item appeared twice following the red square language cue, and twice following the blue square language cue. Participants were randomly assigned to one of the nine lists.

Finally, experimental trials were pseudorandomized across the three emotion conditions, such that a total of twenty-seven lists with different pseudorandom orders were created for cued picture naming.

[1] One list in each emotion condition failed to follow this constraint due to experimenter error. Within each subsection in these lists, the switch rate for each item ranged from 0 to 50%. These lists were not excluded from the data analysis because the overall switch rate for each subsection was 25%.

Emotion induction procedure

A blocked design was used to induce a sustained emotional state. The order of the three emotion blocks (negative, positive, and neutral) was counterbalanced across the participants. A standard emotion-induction procedure involving music and guided rumination was used (Guo et al., 2020; Jefferies et al., 2008).

Specifically, in the positive and negative induction conditions, participants were instructed to develop a particular emotion by listening to music and generating matching thoughts; for example, think about happy events while listening to the happy music. In the neutral induction, participants listened to neutral music and simultaneously imagined a series of mundane activities, such as shopping for groceries, doing small tasks at home, and calling a family member (Birk et al., 2011). Each emotion induction procedure lasted 8 min, and then the picture naming task began. A shorter version of this procedure was repeated for a 2-min "booster'' between the 4-min single-language naming section and the first 4-min mixed-language naming subsection and between the two mixed-language naming subsections in each emotion condition. The relevant music was played at half volume during the remainder of the experiment (Guo et al., 2020; Jefferies et al., 2008; Rowe et al., 2007; Spachtholz et al., 2014; van Steenbergen et al., 2010).

Participants were required to report their emotional states "right now, at this very moment" whenever a 9 × 9 Affect Grid appeared on the screen (eight times per emotion condition). In each emotion condition, participants made their first ratings (Grid 0) before the 8-min emotion-induction procedure. The remaining time points of ratings (Grid 1–7) preceded and followed each of the four naming subsections. Participants were fully debriefed at the end of the experiment.

Data analysis

The naming language was coded for the voluntary mixed-language task, and the trial type (switch or nonswitch) was coded afterward. For both voluntary and cued tasks, accuracy was scored as follows: (A) no or late response; (B) correct response; (C) correct language but wrong word (e.g., *cake* instead of *bread*); (D) wrong language (only for the single-language and cued mixed-language condition); (E) hesitations, utterance repairs, partial responses, or coughing; (F) combination of two languages (e.g., *hou[zi]-monkey)*; (G) responses in the mixed-language condition that could not be classified as a switch or nonswitch trial because they were preceded by trials of no response, or trials of Type F or I; (H) reaction times recording failures; (I) audio recording failures. Notably, some trials violated multiple criteria. For all RT analyses, we only included trials of Type B. For the accuracy analyses, we only excluded trials of Type I. Trials of Type A, C, D, E and F were coded as incorrect. To calculate the switch rate in the voluntary mixed-language condition, we divided the number of switch trials by the total number of mixed-language trials (except responses that could not be classified as switch or nonswitch trials).

Statistical analyses were conducted in R (version 4.1.2). We first checked the efficiency of the emotion induction procedure. The ordinal pleasure and arousal rating data were submitted separately to cumulative link mixed models (CLMM; package ordinal; Christensen, 2022). The model had treatment-coded fixed effects of Emotion block (baseline level: *neutral*) and Grid (baseline level: *Grid 0*) and sum-coded fixed effect of Task (cued $= -1$, voluntary $= +1$) as well as their interactions. The initial models were fitted with a maximal random effects structure (Barr et al., 2013): random intercepts for participants and slopes for all within-participant predictors. If this model did not converge, we built down the random-effects structure by removing the random slopes stepwise and compared the fit of models using the likelihood ratio test. The model reduction was stopped when it resulted in a loss in goodness of fit ($p < 0.20$) (Matuschek et al., 2017) unless the model continued to show convergence issues. Next, we removed non-significant fixed effects based on the likelihood ratio test. The model reduction was stopped when there was a significant deterioration in model fit ($p < 0.05$). For statistically significant interactions, follow-up pairwise comparisons were computed (EMMEANS; package emmeans; Lenth et al., 2022), with *p* values corrected for multiple comparisons using Tukey.

Then, we performed analyses on picture-naming data. Reaction times (RTs) data were submitted to the linear mixed-effects model (LMER; package lme4; Bates et al., 2015), and the switch rate data were submitted to the logistic mixed-effects model (GLMER; package lme4; Bates et al., 2015). Accuracy was close to the ceiling (Table A.1, Appendix A) for both task groups and was not analyzed further. RTs were log-transformed to better approximate a normal distribution.

One model (only including blocked and nonswitch trials) was constructed to examine the mixing costs and one (only including nonswitch and switch trials) to examine the switching costs, the RLDE, and switch rates. For RTs analyses, Emotion block (neutral, positive, negative), Language (L1, L2), Trial type (switching model: switch, nonswitch; mixing model: blocked, nonswitch), Task (cued, voluntary), and their interactions were included as fixed effects. The levels of factor Language and Trial type were coded in proportion to their presence in the data so that the average weighted value was 0 (Declerck et al., 2020) (switching model: L1 = -0.592, L2 = +0.408; nonswitch = -0.273, switch = +0.727; mixing model: L1 = -0.575, L2 = +0.425; blocked = -0.591, nonswitch = +0.409). The emotion block was treatment coded with *neutral block* set as the baseline level, as we were mainly interested in whether the neutral block differed from the other two (negative and positive) blocks (for a discussion about using a priori contrasts to code fixed effects, see Schad et al., 2020). The factor Task was treatment-coded with *voluntary task* and *cued task* set as the baseline levels, respectively, in order to estimate the emotional effects in each task group. When analyzing the switch rate in the voluntary task group, Emotion block (neutral, positive, negative), Language (L1, L2), and their interaction were included as fixed effects. Emotion block was treatment-coded (baseline level: *neutral*). The levels of factor Language were coded in proportion to their presence in the data (L1 = -0.674, L2 = +0.326). The initial models were fitted with a maximal random effects structure (Barr et al., 2013): random intercepts for participants and items and slopes for all within-participant/item predictors. When this model did not converge, correlations between random slopes were removed. If this was not sufficient, random slopes accounting for less than 1% of the variance of their associated random factors were identified and removed simultaneously. All models converged following this procedure. For models with significant fixed effects, *p* values were provided by the summary function of the package LmerTest (Kuznetsova et al., 2017). Only significant results ($p < 0.05$) are discussed in the main text; see Appendix B for the discussion of marginally significant effects ($p < 0.10$).

Results

Emotion manipulation check

Ratings were incomplete for three participants in the voluntary task group and two in the cued task group.[2]

There was a significant interaction between Grid and Emotion Block for both pleasure and arousal ratings [pleasure: χ^2 (14) = 735.75, $p < 0.001$; arousal: χ^2 (14) = 91.31, $p < 0.001$]. Follow-up contrasts showed that there were no significant emotion block differences for pleasure and arousal ratings at baseline (Grid 0) (all $|z|$s < 0.09, all *ps* > 0.23). After the initial emotion induction procedure (Grid 1–7), the positive compared to the neutral block showed higher levels of pleasantness and arousal (all $|z|$s > 3.06, all *ps* < 0.01). The negative compared to the neutral block showed lower levels of pleasantness during the naming task (Grid 1–7) (all $|z|$s > 7.58, all *ps* < 0.001), though the two blocks did not differ for arousal ratings (all $|z|$s < 0.91, all *ps* > 0.63). The results indicated that the emotion manipulations effectively induced the presumed emotional states (Paul & Pourtois, 2017; Vanlessen et al., 2015), at least in the pleasure dimension.

Importantly, all interactions with the task group did not reach significance and were dropped in the model complexity reduction,[3] indicating comparable responses to emotion manipulations in the two task groups.

Emotional effects on bilingual language production

To trim outliers, we discarded RTs below 200 ms. Then, RTs more than 2.5 SD above or below the mean (of the RTs per participant, emotion block, trial type, and language; 2.76% of correct trials in the cued task group; 2.53% in the voluntary task group) were removed.

Reaction times – Reversed language dominance effect and switching cost

Table 2 shows the results from the switching analysis. Fig. 2 presents performance in L1 vs. L2 in different conditions separately, and Fig. 3 shows performance in nonswitch vs. switch trials in different conditions separately. For clarity, before looking into the emotional effects on bilingual language production, we first report the presence of top-down signatures of language control in neutral conditions.

RLDE and switching cost in neutral conditions. Under the *Neutral, Cued task group* and *Neutral, Voluntary task group* baselines, the significant

[2] In the voluntary task group, scores on Grid 0 and Grid 1 in the neutral block and Grid 0 in the negative block were missing for one participant. For the other two participants, scores on Grid 0 in the neutral block and Grid 1 in the negative block were missing, respectively. In the cued task group, due to unexpected programming errors, scores on Grid 5–7 (along with the picture-naming data in the mixed-language section) in the positive block were missing for one participant. Scores on Grid 6 and Grid 7 (along with the picture-naming data in the mixed-language section) in the positive block were missing for another participant.

[3] The only exception is the Grid and Task interaction for the pleasure ratings [$\chi 2$ (7) = 37.62, $p < 0.001$]. Follow-up contrasts showed the cued compared to the voluntary task showed lower levels of pleasantness during the mixed-language section (Grid 5–7: all $|z|$s > 1.93, all *ps* ≤ 0.05), but not before the mixed-language section (Grid 0–4) (all $|z|$s < 1.10, all *ps* > 0.27). Moreover, in the cued task, participants rated decreased levels of pleasantness after than before the mixed-language picture naming (Grid 5 versus Grid 0–4: all $|z|$s $\geq$ 3.01, all *ps* ≤ 0.05; Grid 7 versus Grid 0–4, 6: all $|z|$s > 3.74, all *ps* < 0.01). However, in the voluntary task, only the pleasure ratings before and after the second emotion booster (Grid 5 versus Grid 6) reached significance ($z = -3.50$, $p < 0.05$). No other comparisons of grids at different time points reached significance. The results suggested that cued language-switching was associated with lower levels of pleasantness than single-language naming (Smith et al., 2020) and voluntary language-switching.

Table 2
Results of the switching models.

Predictor	Estimate	SE	t
Intercept: Neutral, Cued task group	**6.608**	**0.018**	**371.74*****
Language	**−0.067**	**0.013**	**−4.98*****
Trial type	**0.034**	**0.007**	**4.81*****
Negative	**0.015**	**0.003**	**4.57*****
Positive	**−0.033**	**0.009**	**−3.45*****
Voluntary	−0.037	0.024	−1.54
Language × Trial type	0.011	0.013	0.87
Language × Negative	−0.010	0.006	−1.57
Language × Positive	0.006	0.008	0.75
Trial type × Negative	−0.010	0.008	−1.26
Trial type × Positive	−0.012	0.008	−1.53
Negative × Voluntary	0.005	0.005	0.10
Positive × Voluntary	0.008	0.013	0.61
Language × Voluntary	0.007	0.013	0.51
Trial type × Voluntary	**−0.020**	**0.009**	**−2.13***
Language × Trial type × Negative	0.009	0.015	0.64
Language × Trial type × Positive	0.015	0.018	0.83
Language × Trial type × Voluntary	0.003	0.018	0.15
Language × Negative × Voluntary	**0.024**	**0.010**	**2.53***
Language × Positive × Voluntary	0.005	0.011	0.44
Trial type × Negative × Voluntary	0.011	0.010	1.07
Trial type × Positive × Voluntary	**0.020**	**0.010**	**1.92†**
Language × Trial type × Negative × Voluntary	−0.013	0.021	−0.62
Language × Trial type × Positive × Voluntary	−0.013	0.024	−0.53
Intercept: Neutral, Voluntary task group	**6.571**	**0.018**	**364.90*****
Language	**−0.060**	**0.013**	**−4.55*****
Trial type	**0.015**	**0.007**	**2.20***
Negative	**0.020**	**0.003**	**5.87*****
Positive	**−0.024**	**0.009**	**−2.61***
Language × Trial type	0.014	0.012	1.13
Language × Negative	**0.014**	**0.007**	**1.99***
Language × Positive	0.011	0.009	1.27
Trial type × Negative	0.001	0.007	0.18
Trial type × Positive	0.008	0.007	1.10
Language × Trial type × Negative	−0.004	0.014	−0.25
Language × Trial type × Positive	0.002	0.017	0.13

Note. † $p < 0.1$; * $p < 0.05$; *** $p < 0.001$.

negative estimates for Language revealed significant RLDE (i.e., slower responses to L1 than L2 trials) in neutral conditions within the cued and voluntary task groups. The significant positive Trial type parameters suggested reliable switching costs within the two groups in neutral conditions. The Language × Trial type parameters were non-significant (all *ps* > 0.26), reflecting no switch cost asymmetry (i.e., the switching costs did not differ between the two languages) in both groups.

Concerning the influence of the task, the significant Trial type × Voluntary parameter indicated that switching costs in neutral conditions differed across the two task groups, with larger switching costs for cued than voluntary task group (see Fig. 3). The Voluntary, Language × Voluntary, and Language × Trial type × Voluntary parameters were non-significant (all *ps* > 0.13), showing that overall RTs, RLDE, and switching cost asymmetry were comparable in the cued and voluntary mixed language blocks.

Emotional effects. Before going to the interactions with the task group, we look into the presence of the emotional effects in each task group. Under the baseline *Neutral, Cued task group*, the significant positive estimate for Negative and negative estimate for Positive revealed overall slower responses under negative than neutral state but overall faster responses under positive than neutral state in the cued task group. However, emotion (i.e., Negative and Positive) did not interact with Language and/or Trial type (all *ps* > 0.11), suggesting that emotion did not significantly modulate RLDE, switching cost, or switching cost asymmetry in the cued task group.

Under the baseline *Neutral, Voluntary task group*, the significant positive estimate for Negative and negative estimate for Positive showed that the voluntary task group responded slower in mixed language blocks under negative than neutral state but responded faster under positive than neutral state. In addition, the Language × Negative parameter was significant, indicating that the RLDE differed across neutral and negative conditions within the voluntary task group. From Fig. 2, we see that the RLDE for this task group was smaller in negative (Language parameter when setting the baseline to *Negative, Voluntary task group*: $E = -0.050$, $t = -3.50$, $p < 0.01$) than neutral ($E = -0.060$, $t = -4.55$, $p < 0.001$) state. Moreover, the decrease in RLDE from a neutral to negative state was mainly attributed to L2 trials. Specifically, the negative state came with slower RTs on L2 trials (Negative parameter when setting the baseline to *Neutral, Voluntary task group, L2*: $E = 0.025$, $t = 6.67$, $p < 0.001$) but did not significantly influence the RTs on L1

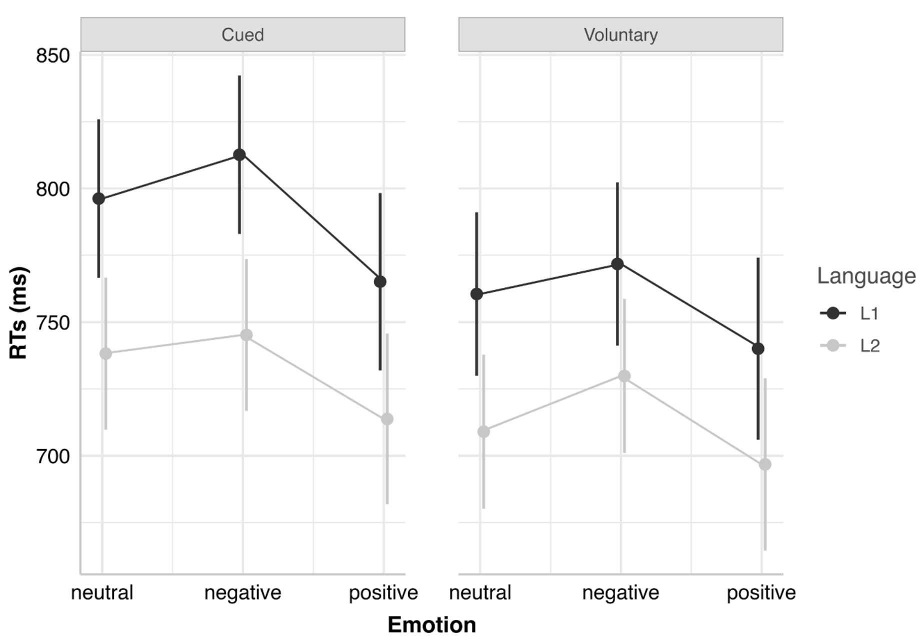

Fig. 2. Estimated reaction times per language (L1 vs. L2), emotion block (neutral vs. negative vs. positive), and task group (cued vs. voluntary). Vertical lines represent 95% confidence intervals.

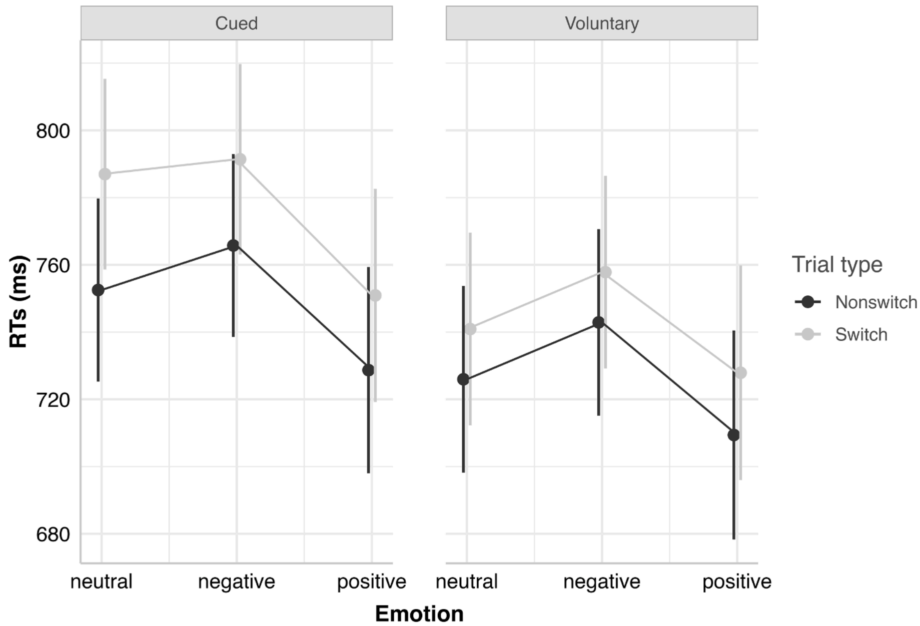

Fig. 3. Estimated reaction times per trial type (nonswitch vs. switch), emotion block (neutral vs. negative vs. positive), and task group (cued vs. voluntary). Vertical lines represent 95% confidence intervals.

Table 3
Results of the mixing models.

Predictor	Estimate	*SE*	*t*
Intercept: Neutral, Cued task group	**6.601**	**0.017**	**384.48*****
Trial type	−0.003	0.008	−0.40
Negative	**0.017**	**0.003**	**5.93*****
Positive	**−0.033**	**0.010**	**−3.21****
Voluntary	−0.022	0.022	−0.97
Language × Trial type	**−0.044**	**0.011**	**−3.87*****
Trial type × Negative	0.003	0.006	0.60
Trial type × Positive	0.011	0.012	0.88
Trial type × Voluntary	**−0.021**	**0.012**	**−1.76†**
Negative × Voluntary	**0.008**	**0.004**	**1.97***
Positive × Voluntary	0.008	0.014	0.54
Language × Trial type × Negative	−0.009	0.011	−0.81
Language × Trial type × Positive	−0.008	0.017	−0.49
Language × Trial type × Voluntary	−0.002	0.017	−0.12
Trial type × Negative × Voluntary	**−0.017**	**0.008**	**−2.04***
Trial type × Positive × Voluntary	−0.018	0.017	−1.03
Language × Trial type × Negative × Voluntary	**0.029**	**0.017**	**1.75†**
Language × Trial type × Positive × Voluntary	0.030	0.025	1.21
Intercept: Neutral, Voluntary task group	**6.578**	**0.017**	**379.13*****
Trial type	**−0.024**	**0.009**	**−2.77****
Negative	**0.025**	**0.003**	**8.27*****
Positive	**−0.026**	**0.010**	**−2.50***
Language × Trial type	**−0.046**	**0.012**	**−3.80*****
Trial type × Negative	**−0.013**	**0.006**	**−2.25***
Trial type × Positive	−0.007	0.012	−0.58
Language × Trial type × Negative	0.020	0.012	1.63
Language × Trial type × Positive	0.022	0.018	1.23

Note. † $p < 0.1$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

trials (Negative parameter when setting the baseline to *Neutral, Voluntary task group, L1*: $E = 0.011, t = 1.90, p = 0.06$). Similar to the cued task group, no emotional effect on switching cost (or its asymmetry) was observed within the voluntary task group (all *ps* > 0.20).

With respect to the interactions with the task group, the significant Language × Negative × Voluntary parameter suggested that the task group modulated the influence of the negative state on RLDE. Indeed, as discussed above, the negative state significantly reduced RLDE in the voluntary task group, but no emotional effect on RLDE was observed in the cued task group. The task group did not significantly modulate emotional effects on switching cost or its asymmetry (all *ps* > 0.05) (for discussion of a marginally significant modulation effect of the task group on the influence of positive state on switching costs, see Appendix B).

In summary, the switching costs were larger in the cued than in the voluntary task group under a neutral state. However, the overall RTs in mixed language blocks, RLDE, and switching cost asymmetry were similar in the two groups (both exhibited RLDE and symmetrical switching costs) under the neutral state. Notably, the influence of the negative state on RLDE was larger for the voluntary than cued task group. Although the negative state significantly reduced RLDE for the voluntary task group, which was mainly attributed to negative state slowing responses on L2 trials, the emotional effect of the negative state on the RLDE was absent for the cued task group.

Reaction times – Mixing effect

The results from the mixing analysis are presented in Table 3. Fig. 4 shows performance in blocked vs. nonswitch trials in different conditions separately. Again, before going into the interactions with emotion, we discuss the presence of language control signatures in neutral conditions.

Mixing effect in neutral conditions. Under the baseline *Neutral, Cued task group*, the non-significant Trial type parameter ($p = 0.69$) and significant Language × Trial type parameter showed an absence of mixing cost and the presence of a mixing cost asymmetry (i.e., a mixing cost for L1 but a mixing benefit for L2, see Fig. 4a) in the neutral state within the cued task group.

Under the baseline *Neutral, Voluntary task group*, the significant negative Trial type parameter suggested a robust mixing benefit (i.e., slower responses to blocked than nonswitch trials) in the neutral state

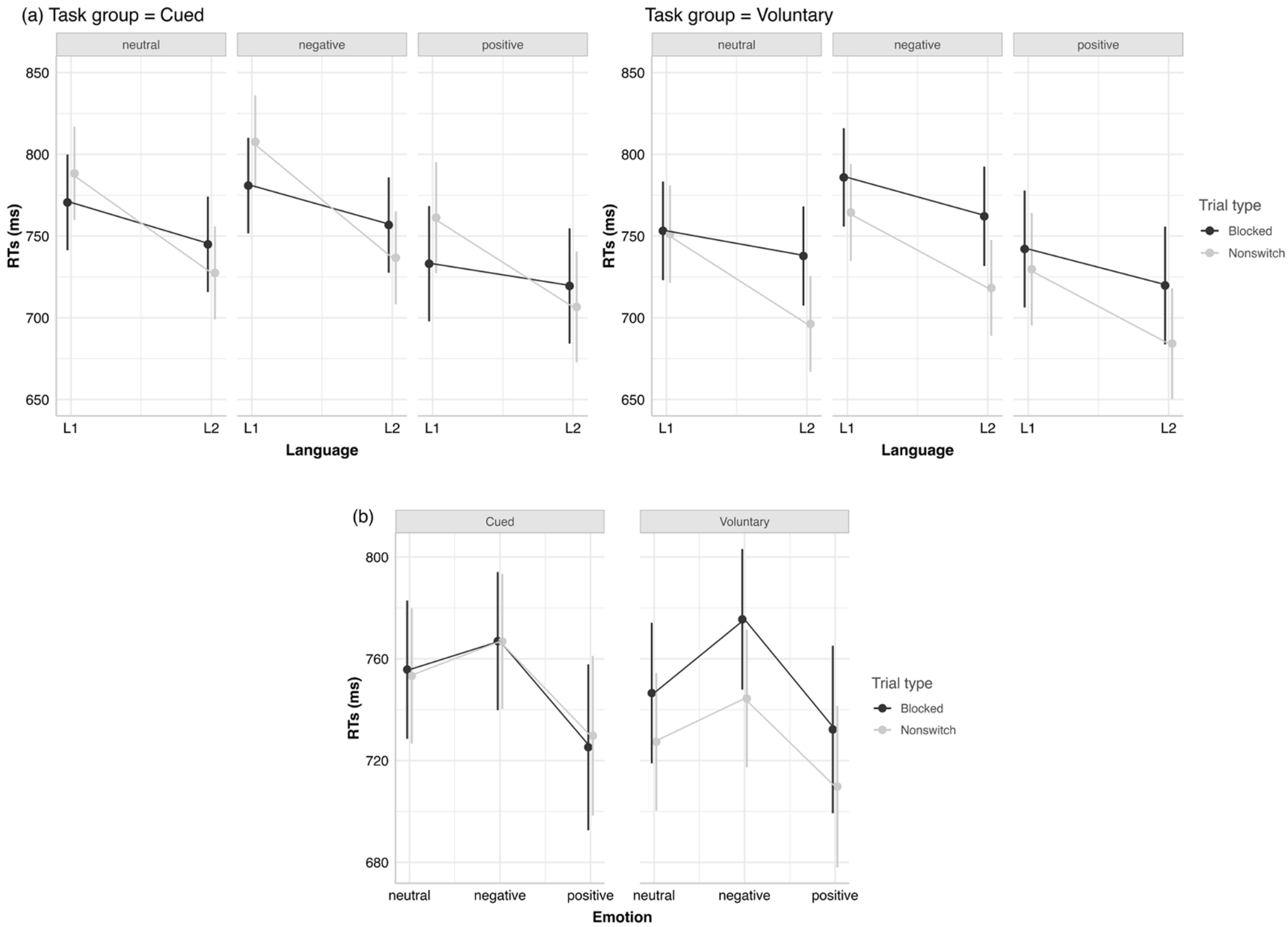

Fig. 4. (a) Estimated reaction times in each trial type (blocked vs. nonswitch) as a function of language, emotion block, and task group; (b) Estimated reaction times in each trial type (blocked vs. nonswitch) as a function of emotion block and task group. Vertical lines represent 95% confidence intervals.

within the voluntary task group. The significant Language × Trial type parameter indicated that the mixing effects differed between the two languages in the neutral state within this group (see Fig. 4a). Follow-up analyses revealed a significant L2 mixing benefit (Trial type parameter when setting the baseline to *Neutral, Voluntary task group, L2*: E = -0.043, t = -4.62, $p < 0.001$), but no significant mixing effect for L1 (Trial type parameter when setting the baseline to *Neutral, Voluntary task group, L1*: E = 0.002, t = 0.23, p = 0.82).

The Voluntary, Trial type × Voluntary, and Language × Trial type × Voluntary parameters were non-significant, suggesting that the two groups were comparable in terms of overall RTs (across nonswitch and blocked trials), mixing effect and its asymmetry in the neutral state (all $ps \geq 0.08$) (for discussion of a marginally significant modulation effect of the task group on the mixing effects in neutral conditions, see Appendix B).

Emotional effects. The significant positive estimate for Negative and negative estimate for Positive under the *Neutral, Cued task group* and *Neutral, Voluntary task group* baselines again showed that the negative state incurred slower overall RTs while the positive state came with faster overall RTs for the two task groups. Under the baseline *Neutral, Cued task group*, no significant interactions between emotion (i.e., Negative and Positive) and Trial type (and Language) were observed (all $ps > 0.37$), reflecting the absence of emotional effects on mixing cost (and its asymmetry) in the cued task group.

Under the baseline *Neutral, Voluntary task group*, however, a significant Trial type × Negative interaction was observed, showing that mixing benefits differed between neutral and negative states in the voluntary task group, with larger mixing benefit for negative (Trial type parameter when setting the baseline to *Negative, Voluntary task group*: E = -0.037, t = -4.33, $p < 0.001$) than neutral (E = -0.024, t = -2.77, $p < 0.01$) condition (see Fig. 4b). As shown in Fig. 4b, the increase in mixing benefit from a neutral to negative state in the voluntary task group was mainly attributed to blocked trials. Specifically, the RTs on blocked trials increased from neutral to a negative state (Negative parameter when setting the baseline to *Neutral, Voluntary task group, Blocked*: E = 0.032, t = 7.34, $p < 0.001$) to a larger extent than RTs on nonswitch trials (Negative parameter when setting the baseline to *Neutral, Voluntary task group, Nonswitch*: E = 0.019, t = 4.85, $p < 0.001$). For the voluntary task group, no emotional effect on mixing benefit asymmetry was observed (all $ps > 0.10$).

Concerning the interactions with the task group, the significant Trial type × Negative × Voluntary interaction suggested that the task group modulated the influence of the negative state on the mixing effect. As shown above, the negative state significantly enhanced the mixing benefit in the voluntary task group. However, no emotional effect on the mixing effect was present in the cued task group. The task group did not significantly modulate the emotional effects on mixing cost asymmetry (p = 0.08) (for discussion of a marginally significant modulation effect of the task group on the influence of negative state on mixing cost asymmetry, see Appendix B).

In summary, under a neutral state, the mixing benefit was significant in the voluntary task group, which was mainly attributed to a mixing benefit for L2. However, the mixing effects, overall RTs (across non-switch and blocked trials), and mixing effect asymmetry were comparable between the two groups in the neutral state. Notably, the negative state was associated with overall slower responses, while the positive state was related to overall faster responses.[4] Moreover, the influence of the negative state on the mixing effect was larger for voluntary than cued task. This emotional effect was absent in the cued task. By contrast, in voluntary task, the negative state enhanced mixing benefit, which was mainly attributed to negative state slowing responses on blocked trials.

Switch rate

The total trial number included for L1 switch, L1 nonswitch, L2 switch, and L2 nonswitch condition was 3062, 3662, 3069, and 10850, respectively. The average trial number per participant for L1 switch, L1 nonswitch, L2 switch, and L2 nonswitch condition was 57 ($SD = 22$), 68 ($SD = 35$), 57 ($SD = 21$), and 201 ($SD = 63$), respectively. Participants, on average, switched on 29.70% ($SD = 11.26$) of the trials in the voluntary mixed-language condition. Across the items that could be classified as switch or non-switch trials, 32.59% ($SD = 12.15$) were named in L1, of which 48.67% ($SD = 16.53$) were switch trials. Of the items named in L2, 23.72% ($SD = 11.67$) were switch trials.

Switch rate analysis revealed a significant main effect of language ($E = -1.254$, $z = -9.11$, $p < 0.001$), with a higher switch rate for L1 ($M = 48.67\%$, $SD = 16.53$) than L2 ($M = 23.71\%$, $SD = 11.67$). However, no emotional effect on the switch rate was observed (all $ps > 0.11$).

Discussion

Everyday bilingual language production often occurs in heightened emotional states. It has long been recognized by psychologists as well as linguists that bilingual language control may be affected by emotional states. However, the available evidence is mostly indirect and far from conclusive. Manipulating bilinguals' emotional states and using prominent markers of top-down language control, the present study aims to offer more compelling evidence for the influence of emotional states on control processes. Moreover, we aim to unravel how the adaptive language control mechanism proposed by the ACH functions in emotional contexts: (1) it operates in exactly the way initially proposed in the ACH (Cognitive effort account), or (2) it adaptively triggers compensatory control processes in the face of emotional disruption of control (Adaptive compensatory control account). Incorporating the emotional states into the ACH, this study would shed light on the (adaptive) control system in more naturalistic settings, which might operate in a more complex way than previously observed by studies that focused solely on social/interactional context. The results reveal that positive state elicits faster overall RTs. Negative state, however, slows overall RTs and increases voluntary mixing benefits (mainly by slowing responses on blocked trials). In addition, negative state reduces RLDE to a larger extent for voluntary than cued task group.

Language control under neutral states

Language switching and mixing performances on the two tasks in neutral state were compared to confirm the assumption that voluntary switching is less effortful than cued switching. Results showed that the two tasks were comparable in overall RTs and mixing effect. Nevertheless, cued switching exhibited larger switching costs than voluntary switching, indicating that it imposed higher demands on reactive control (de Bruin et al., 2018). The results confirmed that voluntary switching could be less costly than cued switching in non-habitual code-switchers (Jiao et al., 2022), though to a lesser degree than previously observed in habitual code-switchers (de Bruin et al., 2018; de Bruin & Xu, 2022; Jevtović et al., 2020).

To better understand the mechanisms of voluntary switching in our bilingual group (i.e., non-habitual code-switchers), a post hoc analysis was conducted to assess whether ease of lexical access was associated with language choice in the voluntary condition. Results revealed that lexical accessibility (in neutral state), operationalized as item-level response-speed difference between L1 and L2 blocked trials (L2 RTs – L1 RTs) (Mooijman et al., 2023), significantly predicted language choice in neutral state.[5] Items named faster in the L2 single-language condition than the L1 single-language condition were named more often in the L2 in voluntary switching, and vice versa for L1 (see also Mooijman et al., 2023). This finding indicated that voluntary switching in our bilingual group was (at least partly) driven by bottom-up processes (i.e., lexical access) (de Bruin et al., 2018). Thus, the voluntary switching condition in the present study engages, at least to some degree, the same mechanisms (e.g., making use of whatever comes most readily and easily to mind) as a dense code-switching context. Note that we do not deny that voluntary switching in our bilingual group may also be influenced by strategic choices in addition to the ease of lexical access. For example, the high proportion of L2 non-switch trials indicated that participants might have strategically adopted L2 as their default language (de Bruin et al., 2018; Mooijman et al., 2023) and prefer to stay in the same default language throughout the mixed-language blocks. Indeed, post hoc analyses showed that while participants switched to L1 more often when items were less accessible in L2 than in L1, regardless of the emotion they experienced, the ease of lexical access did not predict whether participants switched to L2 or stayed in L2.[6]

Whether and how emotional states influence bilingual language control

Our first research question concerned whether and how emotional states influence control processes. In line with our hypothesis, we observed that negative state impaired (proactive) language control, whereas positive state might facilitate (proactive) language control.

Specifically, the negative state came with smaller RLDE (in voluntary switching) relative to the neutral state. Previous research (Stasenko et al., 2021; Weissberger et al., 2012) has observed smaller RLDE in aging relative to younger bilinguals. Coinciding with increased language intrusion errors in mixed-language blocks, smaller RLDE in aging bilinguals was taken as evidence of a language control deficit (Stasenko et al., 2021). Accordingly, we infer that smaller RLDE in the negative state reflects reduced efficiency of (proactive) language control in mixed-language blocks. This interpretation is further supported by the overall slower responses (i.e., less efficient overall performance, Declerck et al., 2020) in negative than neutral state, regardless of whether the overall slower RTs provide independent evidence for

[4] The main effect of Emotion (negative vs. neutral) was modulated by a two-way interaction with Task group, as well as a three-way interaction with Task group and Trial type. This reflects the fact that negative state slows RTs to blocked trials to a larger extent for voluntary than cued task group. This unexpected effect is discussed in Appendix B.

[5] This model included Language choice (L1 scored as 0) as the dependent variable and Trial type (sum coded: nonswitch = −0.298, switch = +0.702), Emotion (treatment coded; baseline level: neutral), Lexical Accessibility (centered and standardized) and their interaction as fixed effects. The Lexical Accessibility parameter reached significance ($E = -0.250$, $t = -4.09$, $p < 0.001$).

[6] The omnibus model included Switch Rate (nonswitch scored as 0) as the dependent variable and Language (sum coded: L1 = −0.676, L2 = +0.324), Emotion (sum coded: negative = −1/0, neutral = 0/-1, positive = +1), Lexical Accessibility (centered and standardized) and their interaction as fixed effects. Only Language × Lexical Accessibility interaction reached significance ($E = -0.141$, $t = -3.15$, $p < 0.01$). Follow-up analyses with L1 and L2 set as the baseline levels for Language revealed a significant main effect of Lexical Accessibility for L1 ($E = 0.102$, $t = 2.97$, $p < 0.01$), but a non-significant main effect of Lexical Accessibility for L2 ($E = -0.013$, $t = -0.54$, $p = 0.59$).

control deficiency (Wu & Struys, 2021) or not. Moreover, we observed that the reduction of the RLDE in negative relative to neutral state was mainly driven by the slowing of the L2. RLDE can be explained with a sustained activation of L2 throughout mixed-language blocks (Declerck, 2020; Declerck & Koch, 2023). Thus, this finding further suggests that the negative state impairs the proactive activation of L2.

In addition, we found that the negative state incurred a larger voluntary mixing benefit than the neutral state. This finding at first appears to suggest that a negative state facilitates proactive control engaged in voluntary mixed-language conditions, which contradicts our prediction. Nevertheless, a closer look at the data revealed that this effect was mainly attributed to negative state slowing responses on blocked trials. Thus, a more plausible explanation for this finding is that the negative state disrupts proactive control engaged in the single-language block (e.g., proactive inhibition of the non-target language in anticipation of only using one target language in the task) (de Bruin et al., 2018).

Furthermore, in both tasks, we observed overall slower responses in negative state but faster responses in positive state. On the one hand, the results probably suggested a general effect of emotional states on language production processes (see Hinojosa et al., 2017, for preliminary evidence for the detrimental effects of negative states on phonological encoding). However, this line of research is still in its infancy, and the evidence is scarce (Chwilla, 2022). On the other hand, this effect may reflect the disruptive effect of negative state but the facilitative effect of positive state on global proactive control. Specifically, as stated above, global RTs on blocked trials have been regarded as a measure of proactive language control (de Bruin et al., 2018). The global performance (e.g., overall RTs) on mixed-language production has also been taken as an index of global proactive control (Wu & Struys, 2021).

In the following paragraphs, we will discuss some of our findings in more detail. The first finding that should be addressed is the differential effects of negative and positive states on language control processes, which resemble findings in cognitive control literature. For instance, cognitive control literature has observed that individuals perform worse on tasks testing global, sustained, and proactive control processes under a negative state (Figueira et al., 2017; Guo et al., 2020; Yang et al., 2018). In contrast, positive state improves performance on proactive control tasks (Chiew & Braver, 2014). Given that domain-general cognitive control processes (e.g., proactive control) were found to be engaged in language control (Jylkkä et al., 2018; Liu et al., 2020), we infer that the differential effects of negative and positive states on language control may at least partially stem from their effects on cognitive control.

The second finding that may be worth discussing is the absence of robust emotional effects on switching costs. One explanation is that the emotional state could have affected the switching costs. However, this effect may be constrained by bilingual language experience, which has been proposed to influence language-switching performance in the laboratory (Green & Abutalebi, 2013). To consider this possibility, we examined the modulation effects of language proficiency (QPT scores and self-rated L2 proficiency averaged across ratings for production, comprehension, reading, and writing) and daily code-switching habits (BSWQ scores) on the emotional effects on switching cost.[7] The results revealed that relative to neutral state, the negative state came with marginally significant larger voluntary switching costs in frequent code-switchers ($E = 0.015$, $t = 1.65$, $p = 0.10$) but incurred marginally significant smaller voluntary switching costs in infrequent code-switchers ($E = -0.019$, $t = -1.80$, $p = 0.08$) (see Figure A.1 in Appendix A) (see Green & Wei, 2014, p. 508, for a related proposal that the emotional effects on control processes show opposite patterns for bilinguals with different language experience). Though it is unclear why daily code-switching habits modulate the emotional effects on switching costs in this sophisticated manner, we contend that participants' relatively broad daily code-switching frequency distribution could at least in part explain the absence of emotional effects on switching costs (i.e., the emotional effects in high- and low-frequency groups might have offset with each other).

The third finding is the absence of emotional effects on switch rates in voluntary mixed-language conditions, which is inconsistent with existing evidence from clinical case studies, self-report studies, and observational empirical studies. Correlation analyses showed that lower switch rates were associated with smaller RLDE [neutral: $r(52) = 0.35$, $p < 0.01$; negative: $r(52) = 0.32$, $p < 0.05$; positive: $r(52) = 0.26$, $p = 0.06$], and the RLDE was found to be reduced by negative state. As such, emotional states might be expected to affect voluntary switch rates. We infer that the switch rate during voluntary switching between single words may be influenced at least in part by bottom-up lexical accessibility (Gollan & Ferreira, 2009), which might have attenuated the emotional effects on switch rates mediated by top-down control efficiency. Indeed, as mentioned in the previous section, post hoc analyses showed that participants switched to L1 more often when items were less accessible in L2 than in L1, regardless of the emotion they experienced. Future research should examine the emotional effects on voluntary language switching during sentence production. High levels of top-down control processes (rather than opportunistic planning) may be engaged in sentence-level code-switches (e.g., alternation and insertion) (Green & Wei, 2014); thus, the rate of switches within or between sentences may be affected by emotional states.

Of note, the intricate language control processes may be susceptible to small changes in task design (de Bruin et al., 2018). For example, post hoc exploratory analyses revealed that the order of L1 and L2 blocked conditions (L1 first vs. L2 first) significantly modulate the mixing effect (larger mixing benefit for L2 first than L1 first group) (see Figure A.2 in Appendix A), though it did not modulate the RLDE or switching cost.[8] Moreover, using a practice phase in the present study might have strengthened the dominance reversal by increasing the accessibility of names from both languages (for a related discussion of the influence of language balance on the RLDE, see Gollan & Ferreira, 2009). Thus, it awaits further investigation whether our findings (e.g., emotional states influence proactive rather than reactive control) hold across different task implementations.

How the adaptive control system operates in emotional contexts

Our second research question examined how the adaptive control system works in emotional contexts by investigating the interaction between switching contexts and emotional states in modulating bilingual language control. According to the cognitive effort account, cued switching imposes higher demands on control processes than voluntary switching. On this view, the emotional effects should be more

[7] Each of the three (centered and standardized) bilingual experience measures was inserted into the switching models in the main analyses separately. The Trial type × Negative × BSWQ scores interaction under the baseline *Neutral, Voluntary task group* was significant ($E = 0.017$, $t = 2.50$, $p < 0.05$). However, all other effects involving the factor Trial type, Emotion, and bilingual experience measure did not reach significance (all $|t|$s < 1.76, all $ps \geq 0.08$). The significant Trial type × Negative × BSWQ scores interaction was explored in separate refitted mixed-effects models by rescaling BSWQ scores 1 SD above/below the mean to examine the Trial type × Negative interaction at high and low values of BSWQ scores (Kheder & Kaan, 2021).

[8] The models included Language (sum coded in proportion to their presence in the data), Trial type (sum coded in proportion to their presence in the data), Block order (sum coded: L1 first = −0.5, L2 first = +0.5) and their interaction as fixed effects. The Trial type (nonswitch vs. blocked trials) × Block order interaction stayed significant regardless of the task group (cued only, voluntary only, or both cued and voluntary) and emotion condition (neutral only or all three emotion conditions) included in the dataset (all $|t|$s > 2.19, all $ps < 0.05$).

pronounced in cued than voluntary switching. However, the adaptive compensatory control account predicts that compensatory control processes are triggered in cued but not voluntary switching. Thus, there should be less emotional disruption (under negative state) in cued than voluntary switching.

Though the cognitive effort account was not supported by the comparison across voluntary and cued switching, the adaptive compensatory control account was supported by the finding that the negative state's detrimental influence on proactive control (i.e., smaller RLDE under negative than neutral state) was more pronounced in voluntary than cued switching. Of note, the demands on proactive control processes underlying RLDE were comparable in the two switching conditions (i.e., similar RLDE under the neutral state); thus, this finding was unlikely to be explained with higher demands on proactive control in voluntary switching. Given that voluntary switching and mixing may engage some form of decision-making (especially in non-habitual code-switchers), it might be argued that the influence of negative state in the voluntary condition is due to its effect on the executive decision. However, RLDE is seldom explained with the burden of executive decision (e.g., deciding whether to switch or stay, or which language to use) (for discussion of costs associated with executive decision in voluntary switching, see Gollan & Ferreira, 2009). Hence, we argue that the executive decision may not be the main mechanism driving the emotional effects in the voluntary context.

Notably, the cognitive effort account did receive critical support from the comparisons across single-language and voluntary mixed-language conditions. Specifically, on the cognitive effort account, relative to the single-language condition, the voluntary mixed-language condition imposes lower demands on control processes and thus reveals less robust emotional effects. However, on the adaptive compensatory control account, voluntary mixed-language condition is more susceptible to emotional disruption than single-language condition where a loss of strict control is in disagreement with the task goal and thus elicits compensatory control processes. In line with the cognitive effort account, we observed that negative state slowed responses to a lesser degree on voluntary nonswitch than single-language trials (thus increasing voluntary mixing benefits). In the meantime, we found significant voluntary mixing benefits under the neutral state, indicating less demands on proactive control in voluntary mixed-language context relative to single-language context (de Bruin & Xu, 2022). Note that there were more trials in the nonswitch than the single-language condition for the voluntary task group (neutral condition: 4559 vs. 3173; negative condition: 4535 vs. 3168; positive condition: 4657 vs. 3232); thus, this effect is unlikely to be an artifact of decreased power to detect emotional effects in the former condition.

Taken together, we argue that both the cognitive effort and the adaptive compensatory control accounts could predict how the adaptive control mechanism proposed by the ACH functions in emotional contexts. Here, we propose that the compensatory mobilization of top-down control would be selectively invoked when a loss of top-down control (under negative states) deviates from the task goal, for example, in cued mixed- and single-language contexts. Yet, this mechanism is less likely to be invoked when the loss of control stays with the task goal, for example, in a voluntary mixed-language context. However, when we investigate the interaction of the effects of emotional states with naming contexts, the role of compensatory mechanisms in cued mixed- and single-language contexts could be observed only when the cognitive effort demands of these two interactional contexts are no greater than those of the voluntary mixed-language context (e.g., during the comparison of the emotional effects on the RLDE in cued switching with those in voluntary switching). Otherwise, the impairment associated with high levels of cognitive effort would mask/outweigh the role of compensatory mechanisms in the cued mixed- and single-language contexts (e.g., when comparing the emotional effects on RTs in the single-language context with those in the voluntary mixed-language context).

Theoretical implications

Based on the results concerning the interaction of emotional states and interactional contexts, we propose that the adaptive control system proposed by the ACH may function in two different, but not mutually exclusive, ways in emotional contexts. Firstly, the control system may adapt to the demands imposed by the interactional context, thus triggering different forms and levels of control processes in different interactional contexts (Cognitive effort account). This is exactly what Green and Abutalebi (2013) initially proposed in the ACH. In emotional contexts, the control processes activated may be influenced by the emotional states. In this case, interactional contexts engaging higher levels of control would be more susceptible to the emotional effects. Secondly, when the detrimental effects of (negative) emotional states on control processes cause (or potentially cause) deviations from the communicative/task goals in certain interactional contexts, the adaptive control system may trigger compensatory adjustments in control to bring behavior more in line with the intended goal (Adaptive compensatory control account).

Our findings extend the ACH in two aspects. Firstly, the results indicate that in addition to the control processes distinguished by the ACH, demands on processes associated with the compensatory mobilization of top-down control (Botvinick et al., 2004) may also vary depending on the social context of the communication. Secondly and more importantly, naturalistic language processing has been proposed to engage complex interactions of diverse types of contexts, including the prior linguistic/discourse context (co-text), social context, and personal context (e.g., emotional states) (Hasson et al., 2018). The ACH and its accumulating evidence (Blanco-Elorrieta & Pylkkänen, 2017) have underscored the social context's influence on bilingual language control. However, it remains understudied how social context interacts with other types of contexts. Incorporating the emotional states into the ACH, this study thus further uncovers the complexities underlying bilingual language control in naturalistic, everyday language use.

One limitation of the present study is that two (cued vs. voluntary) switching contexts were manipulated between participants since the voluntary switch rate of our bilingual group is unknown and should be examined first before setting the switch rate in the cued condition accordingly. Future studies should replicate the findings regarding the modulating role of switching context using a within-participant design. In addition, given that the arousal ratings did not differ between negative and neutral conditions, we can be reasonably confident that the detrimental effects of negative conditions stemmed from the valence dimension of emotion (negative versus positive). However, since the positive condition elicited higher arousal levels than the neutral condition, it is unclear whether the facilitative effects of the positive condition and the differential effects of negative and positive conditions are attributed to the valence or arousal dimension of emotion. Future research may disentangle the effects of valence and arousal on language control.

Conclusion

The present study investigates whether and how emotional states influence bilingual language control and how the effects of emotional states and switching contexts interact. The results revealed that the negative state impaired proactive language control while the positive state seemed to improve proactive language control. Most importantly, we observed that the negative state's detrimental influence on control processes could increase proportionally with the levels of control engaged in the interactional contexts. Meanwhile, the control system might adaptively compensate for the detrimental effects of negative emotional states according to the communicative goals in the interactional contexts. These findings reflect the complexities underlying adaptive language control in emotional contexts, and extend the predictions of the ACH.

CRediT authorship contribution statement

Siyi Jiang: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yujie Meng:** Resources, Investigation. **Baoguo Chen:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data and analysis code are available at: https://osf.io/k9xrt/.

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Appendix A. Supplementary data

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