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Interactive Model of Executive Functions to Understand Error Correction

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Abstract

This article reports an investigation aimed at analyzing an interactive model of executive functions, which seeks to explain the process followed by human beings to correct their mistakes. The method followed was an analysis based on structural equations, considering the maximum likelihood process around a model that considered six executive functions. We worked with a randomized sample of 771 subjects (mean age = 39.86, SD = 15.47; 50.5%, women, 50.50%). The findings suggest that error correction is a complex executive function as it is the product of the internal language capacity that regulates behavior and cognition, adequate regulation of the limbic system, adequate decision-making, and control of automatic impulses, determining how to act and verify the thoughts and behavior of the subject. The contribution of the proposed theoretical model lies in understanding the process by which human beings manage to correct errors. In addition, how this explanatory model could help neuropsychological intervention processes to work on this cognitive ability in individuals with difficulties in correcting errors.

Keywords:

Decision-Making; Error Correction; Executive Functions; Frontal Lobe; Inhibitory Control; Neuropsychology; Structural Equation Modeling.

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1- Introduction

There are three levels to observe the control of human behavior. The first level is a completely automatic form of behavior, potentially related to basic cognitive systems. The second level is semi-automatic behavior control, through which a human being can act according to previously learned habitual patterns. Finally, the third level is based on the fully conscious control of regulated behavior controlled by executive functions [1-3].

Executive functions are high-level mental abilities that allow human beings to plan for and project into the future, make correct decisions, and collect relevant visuospatial, episodic, and phonological information in their working memory. Consequently, this allows one to solve problems, monitor and supervise behavior, regulate emotions, achieve goals with creative behavior and within socially accepted parameters, anticipate the consequences of behavior, control impulses, act with initiative, correct mistakes, and be flexible when solving tasks, among other high-level skills [4-8].

Executive functions are widely related to the most developed structure of the nervous system, the prefrontal cortex [9, 10]. In this sense, studies have found that the ventromedial and dorsolateral prefrontal cortex account for the executive functions concerned with goal-directed behavior and metacognitive abilities [11, 12]. The right ventrolateral prefrontal cortex is related to the inhibitory control of automatic impulses [13], and the cortex of the anterior cingulum is associated with the abilities of supervision and monitoring of behavior, cognitive control, executive attention, and analysis of the conscious behavioral response [14].

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This research focuses on the ability to correct an error as one of the mental abilities mentioned previously. Today, not all human beings can evidence this executive function; in addition, regulated and goal-directed behavior depends to a large extent on the ability to correct mistakes made on a day-to-day basis [15]. The ability to correct errors is an executive function belonging to the metacognitive system of the human brain. When an error is detected, this ability triggers a series of neuropsychological sub processes, such as the behavior monitoring system. However, there is no clarity about the interactions followed by different executive functions to fulfill this purpose. Within the proposed context, this research introduces an interactive model of executive functions, which seeks to contribute to the understanding of the cognitive processes that humans follow when correcting an error [7]. There have been studies on error correction in various contexts. For example, tasks have been carried out in the population of individuals with autism and neurodevelopmental disorders, where verbal instructions are generated to develop the ability to correct errors in favor of labor competencies [16-18], and the effectiveness of the use of audiovisual resources to improve error correction in daily life has been also analyzed [19].

In the cognitive context, different areas have been analyzed, such as the contribution of teamwork to generating mental flexibility in favor of error correction [20], the impact of prior knowledge of a certain problem and its relationship with the ability of adults to correct an error [21], and the presence of feedback on a problem and its contribution to the ability to correct errors [22]. In the motor context, areas such as the role of monitoring and the motor activation threshold in correcting errors have been analyzed [15]. When correcting an error in a motor pattern, the main error has a significant impact on the movement pattern of the secondary error. However, the global motor pattern of the individuals can benefit from the correction of the first link [23]. At the neurofunctional level, the role of the left premotor cortex has been described in the ability for conscious correction of an error with both hands [24]. Finally, there have been several case reports at the level of stimulation in favor of error correction, including the greater implication of auditory sensory information over visual information when an individual must correct an error [25] and the importance of visual feedback in the error correction ability [26-28].

In summary, previous research on error correction has clarified the possibility of its improvement through interventions or the influence of various factors on its effectiveness. However, no research has investigated the potential cognitive dynamics before correcting an error. In addition, there is a new interest in deepening executive functions, leading to a new era of research on executive functions, where it can continue to contribute to its theoretical and empirical construction in a broader understanding of these mental abilities in the regulation and control of behavior [3]. In this context, the contribution of this research lies in a clearer understanding of the dynamics encompassing the ability to correct errors in humans. Besides, the proposed model allows for the application of neuropsychological intervention processes to provide neuropsychological treatment to human error correction capacity. This research aims to contribute to the understanding of the executive mechanisms related to the ability to correct errors through a proposed interactive model of executive functions.

1-1- Research Hypotheses

Based on the literature review on various classic neuropsychological theories, such as those proposed by Luria [29-31], Barkley [6, 7], Norman and Shallice [32], Damasio [15], Miyake et al. [33], and Diamond [16], it is hypothesized that various executive functions could help to understand the ability to correct errors in human beings. For example, the inhibitory control of automatic responses allows for the conscious control of linguistic, emotional, cognitive, and behavioral skills that significantly affect the ability to correct errors [34, 35]. Based on this statement, this paper proposes the following hypotheses:

H1. Inhibitory control of automatic responses positively affects internal language-regulating behavior and cognition.

H2. Inhibitory control affects the regulation of the limbic system.

H3. Inhibitory control affects decision-making.

H4. Inhibitory control affects error correction.

The internal language is another executive function with an influential role in the ability to correct errors, which permits the monitoring of behavior and cognition. This ability helps the individuals generate the necessary instructions to avoid repeating a mistake, make correct decisions, and consequently avoid errors [36]. Based on this statement, the following hypotheses were raised:

H5. The internal language that regulates behavior and cognition influences the regulation of the limbic system.

H6. Regulation of the limbic system influences decision-making.

The ability to make decisions is another function of the frontal lobe that plays a critical role in human behavior because it has an impact when it is verified that the individuals have the opportunity to correct errors through actions being carried out [37]. The hypotheses that arise from this statement are as follows:

H7. Decision-making affects the verification of cognitive and behavioral activity.

H8. Decision-making affects error correction.

Verification executive function acts at a metacognitive level, in which it validates that the cognitive and behavioral processing of individuals would lead them toward the previously set objectives, positively influencing their ability to correct an error [32].

H9. The verification of cognitive and behavioral activity influences error correction.

Therefore, various executive functions affect the correction capacity of human beings. Consequently, this research aims to explain its complexity by proposing an explanatory model that includes relationships to clarify its dynamics (Figure 1).

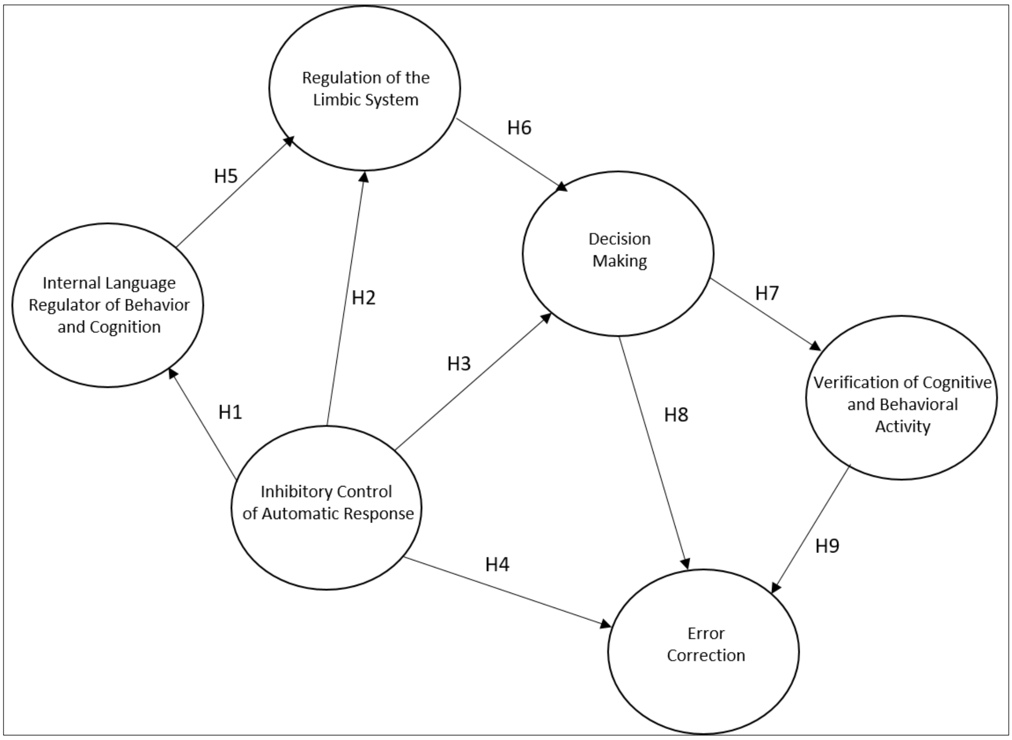

Figure 1. Diagram of the hypothesized error correction mode

2- Materials and Methods

2-1- Sample

A random sample of 771 participants with a mean age of 39.86 (SD = 15.47) was selected from 134 neighborhoods in the metropolitan area of Quito, Ecuador. The proportion of participants and the instrument applied was 40.57 participants per instrument (see Appendix I). Table 1 presents the descriptive statistics characterizing the research sample. The participation criteria in the research consisted of the following: living in the metropolitan area of Quito, not presenting a history of mental illness, understanding the content of the instrument applied, being of legal age, and signing the consent form for voluntary participation. The exclusion criteria were the following: presenting a psychopathological disorder, possessing a disability, and unwillingness to participate in the research.

Table 1. Characteristics of the Sample (N = 771)

Variable	(%)
Gender	
Women	50.5%
Men	49.5%
Age (year)	
Younger than 26	23.6%
26-45	41.6%
46 years and above	34.8%
Educational level attained	
Incomplete secondary level or less	14.5%
Complete secondary level	48.5%
Incomplete university level	18.3%
Undergraduate/postgraduate university level	18.7%

2-2- The Study Scenario

This investigation was carried out in Quito, the capital of Ecuador. This city uses the United States dollar as its official currency, and it is a Western-type capitalist economic context. The population of Quito is approximately three million, the majority of whom are Catholic. The metropolitan area of the city has access to high-level education, basic services, technology, and healthcare, like other large metropolises in the world [38, 39]. These sociodemographic characteristics allowed us to consider the following results, not only for the context in which they were found but also for similar contexts with these characteristics.

2-3- Measurements

This research applied the EOCL-1 scale [40]. The executive functions measured with the scale were as follows: internal language regulator of behavior and cognition, regulation of the limbic system, decision-making, verification of cognitive and behavioral activity, inhibitory control of automatic responses, and error correction. It is also a free-use scale (Table A1: Appendix I).

2-4- Procedure

This study started with the approval of the ethical committee of the Indoamerica University from Ecuador. The instrument application was conducted at each participant's house according to the randomized assignment. The participants provided their informed consent for voluntary and anonymous participation. Throughout the study, the participants' physical and psychological integrities were safeguarded. Once the instruments were applied, the data was registered and organized in databases for future statistical analysis. Figure 2 shows the flow chart of the applied research method.

Figure 2. Flowchart of the investigation carried out

2-5- Statistical Analysis

Statistical techniques of central tendency and dispersion were applied for descriptive analysis. Cronbach's alpha and Pearson's correlation were applied to analyze the internal consistency and identify the association between the evaluated variables, respectively. Multiple linear regression was utilized to analyze the predictive role of executive functions concerning error correction. Finally, the analysis of structural equations and the invariance of the hypothesized model were applied, considering the interpretation values of CFI $\geqslant 0.95$, RMSEA < 0.06, SRMR $\leqslant 0.08$ [1]. The analysis was performed using the statistical packages SPSS v. 25 and Amos v. 23.

3- Results

Table 2 presents the descriptive values of the six executive functions measured in the research.

Table 2. Descriptive Analysis

	Min	Max	Median	Standard Deviation	Asymmetry	Kurtosis
Internal Language Regulator of Behavior and Cognition	3.00	15.00	12.16	2.46	-1.15	1.85
Inhibitory Control of Automatic Responses	4.00	20.00	16.80	2.55	-0.83	1.03
Error Correction	5.00	15.00	12.92	1.78	-0.65	0.24
Decision-Making	3.00	15.00	13.10	1.78	-0.96	1.78
Regulation of the Limbic System	3.00	15.00	11.48	2.54	-0.80	0.68
Verification of Cognitive and Behavioral Activity	4.00	15.00	12.90	1.89	-0.95	1.06

The internal consistency analysis revealed acceptable reliability values in the measurement of each of the variables evaluated. The correlation between the items of each executive function ranged from medium to large. Finally, most of the sociodemographic variables were not associated with executive functions except for decision-making and marital status and also verification and age. Table 3 shows the above-mentioned results.

Table 3. **Scale Confidence**

Executive Function	Cronbach Alpha	Correlation	Genre	Civil Status	Age
Verification of Cognitive and Behavioral Activity	0.83	$r = \geq 0.67$ $p = < 0.001$	$x^2 = 14.55$ $p = 0.20$	$x^2 = 49.07$ $p = 0.27$	$r = -0.09$ $p = 0.01$
Internal Language Regulator of Behavior and Cognition	0.82	$r = \geq 0.70$ $p = < 0.001$	$x^2 = 112.85$ $p = 0.30$	$x^2 = 52.50$ $p = 0.18$	$r = 0.06$ $p = 0.10$
Inhibitory Control of Automatic Responses	0.70	$r = \geq 0.42$ $p = < 0.001$	$x^2 = 8.04$ $p = 0.88$	$x^2 = 53.60$ $p = 0.56$	$r = -0.01$ $p = 0.68$
Decision-Making	0.76	$r = \geq 0.53$ $p = < 0.001$	$x^2 = 9.30$ $p = 0.59$	$x^2 = 74.65$ $p = 0.003$	$r = -0.02$ $p = 0.47$
Regulation of the Limbic System	0.83	$r = \geq 0.66$ $p = < 0.001$	$x^2 = 6.96$ $p = 0.86$	$x^2 = 48.87$ $p = 0.44$	$r = 0.05$ $p = 0.18$
Error Correction	0.73	$r = \geq 0.51$ $p = < 0.001$	$x^2 = 8.55$ $p = 0.48$	$x^2 = 38.31$ $p = 0.36$	$r = -0.03$ $p = 0.34$

The correlation between the different executive functions showed statistically significant relationships at a range of small to medium in magnitude (Table 4). Subsequently, the prediction of the correction of errors in a multiple linear regression was analyzed, considering the following executive functions as independent factors: internal language regulator of cognition and language, regulation of the limbic system, decision-making, and verification of cognitive activity and behavioral and inhibitory control of automatic responses. There was a prediction of 35% of the variance of the error correction variable (Table 5).

Table 4. **Executive Function Correlation**

	1	2	3	4	5	6
1. Internal Language Regulator of Behavior and Cognition	1					
2. Inhibitory Control of Automatic Responses	0.30 < 0.001	1				
3. Error Correction	0.31 < 0.001	0.48 <0.001	1			
4. Decision-Making	0.31 <0.001	0.34 < 0.001	0.41 < 0.001	1		
5. Regulation of the Limbic System	0.22 < 0.001	0.36 < 0.001	0.30 < 0.001	0.29 < 0.001	1	
6. Verification of Cognitive and Behavioral Activity	0.31 < 0.001	0.31 < 0.001	0.42 < 0.001	0.42 < 0.001	0.24 < 0.001	1

Table 5. **Error Correction Multiple Prediction**

Dependent Variable	Predictive Variable	β	Std. Error	β Standardized	t	Sig.	Adjusted R^2
Errors Correction	Constant	3.28	0.49			< 0.001	0.35
	Internal Language Regulator of Behavior and Cognition	0.06	0.02	0.08	2.76	0.006	
	Inhibitory Control of Automatic Responses	0.21	0.02	0.30	9.06	< 0.001	
	Decision-Making	0.17	0.03	0.17	5.15	< 0.001	
	Regulation of the Limbic System	0.05	0.02	0.07	2.29	0.022	
	Verification of cognitive and behavioral activity	0.19	0.03	0.21	6.14	< 0.001	

The structural equations of the interactive model of executive functions explained the dynamics of the ability to correct human errors. As shown, the tested model presented adequate levels of adjustment based on the following values: χ^2 (142) = 315.60, p = 0.001, CFI = 0.96, SRMR = 0.04, TLI = 0.96, RMSEA=0.04 (0.03 HI - 0.04 LOW). Figure 3 depicts the model.

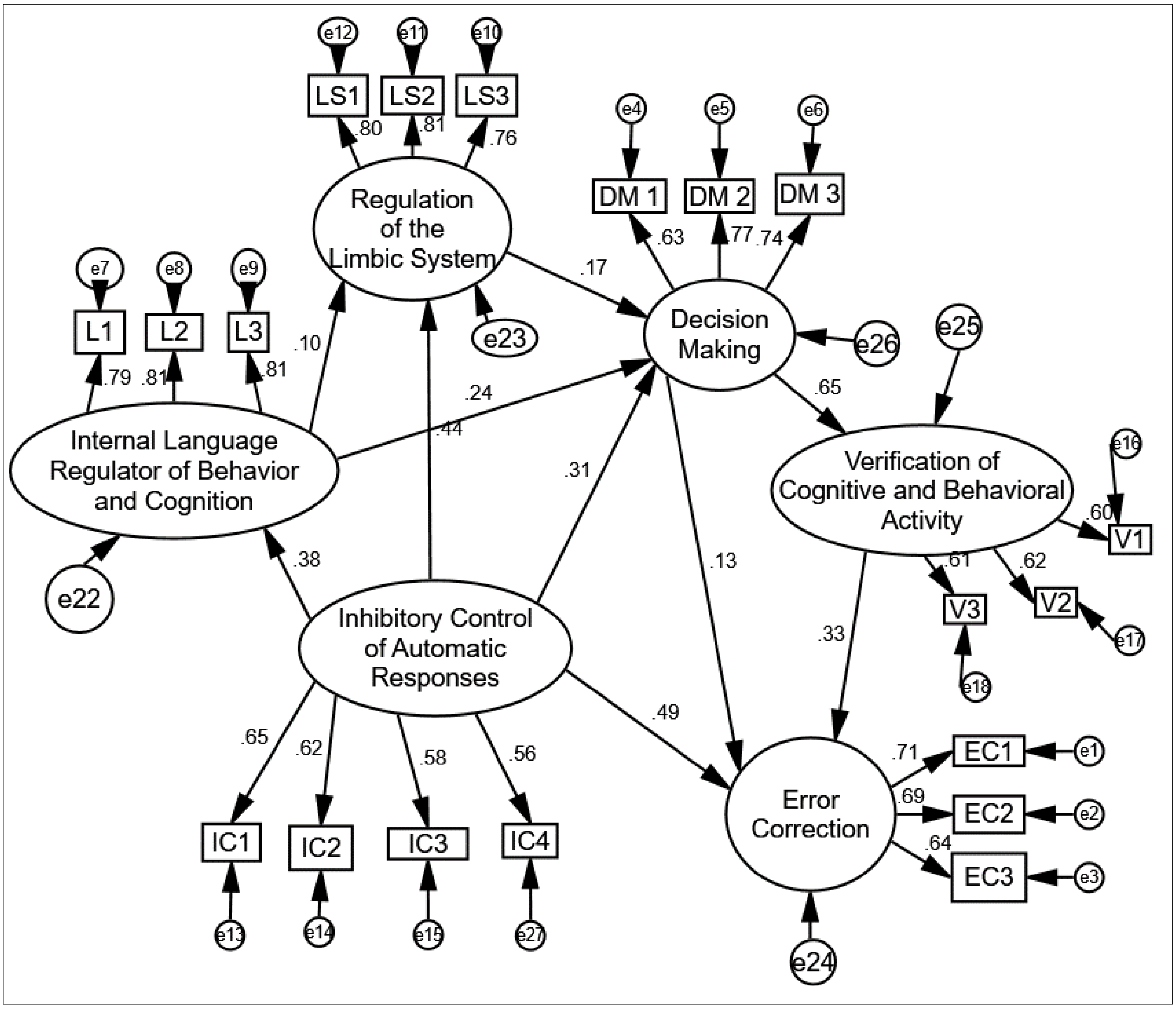

Figure 3. **Interactive model of error correction with the interaction of executive functions**

The non-standardized regression weights showed statistically significant values in the paths proposed in the model, except for the path between decision-making and error correction. It is noteworthy that this path was maintained because of its explanatory value as a significant contributor at the theoretical neuropsychological level. Although it was possible to eliminate this path to improve the statistical value of the model, the research team decided to preserve it to complete the theory (Table 6).

Table 6. **Non-standardized Regression Weights**

			Estimate	*S.E.*	*C.R.*	*p*
Internal Language Regulator of Behavior and Cognition	←	Inhibitory Control of Automatic Responses	0.53	0.07	7.77	***
Regulation of the Limbic System	←	Internal Language Regulator of Behavior and Cognition	0.10	0.05	2.09	**
Regulation of the Limbic System	←	Inhibitory Control of Automatic Responses	0.62	0.08	7.97	***
Decision-Making	←	Internal Language Regulator of Behavior and Cognition	0.15	0.03	5.23	***
Decision-Making	←	Regulation of the Limbic System	0.10	0.03	3.34	***
Decision-Making	←	Inhibitory Control of Automatic Responses	0.27	0.05	5.08	***
Verification of Cognitive and Behavioral Activity	←	Decision-Making	0.74	0.07	9.98	***
Error Correction	←	Verification of cognitive and behavioral activity	0.32	.07	4.49	***
Error Correction	←	Inhibitory Control of Automatic Responses	0.47	0.06	8.25	***
Error Correction	←	Decision Making	0.15	0.08	1.77	0.08

*** < 0.001 ** < 0.01 * < 0.05

The gender variable was considered in the comparison models to analyze the invariance of the proposed model. First, the unrestricted or configurational model was estimated, applying the same form of the model for both men and women without any equivalence restriction between parameters. Then, a second model was estimated, keeping all the factorial loads of the indicators equal across the groups. Finally, the third model also considered the structural coefficients of the trials equal across the groups in addition to the restrictions of the second model. The first model was the basis of comparisons.

The criteria according to Byrne [11], Chen [12], and Cheung and Rensvold [13] were chosen for the comparisons between models and the variations of CFI and RMSEA (ΔCFI and ΔRMSEA) due to less sensitivity of CFI and RMSEA to the sample size compared to chi-square (χ^2). Based on the recommendations of the authors, the cut-off points to support the invariance were set to a maximum change in the absolute CFI value of 0.010 and a maximum change in the absolute RMSEA value of 0.015. Table 7 shows the values of ΔCFI and ΔRMSEA resulting from comparing Models 2 and 3 against Model 1. In all cases, they generated values lower than the selected cut-off points. These results support the invariance of the model; that is, the proposed model is supposed to be equivalent for both men and women.

Table 7. Invariance Analysis Fit Statistics

Model	Comparison	Chi square (χ^2)	Df	RMSEA	ΔRMSEA	CFI	ΔCFI
Model 1: Unrestricted or configurational		603.308	284	0.038		0.934	
Model 2: Equal factorial loads	2 vs. 1	628.209	297	0.038	0	0.931	-0.003
Model 3: Factor loads and equal structural coefficients	3 vs. 1	652.298	307	0.038	0	0.929	-0.005

4- Discussion

The body of research on the dynamics that explain the error correction process is still under development; therefore, this study contributes through the proposal of a theoretical interactive model of executive functions seeking to play a role in understanding this mental ability. The results showed that the proposed model had adequate goodness of fit for the hypothesized relationships, which is consistent with previous research and thus supports the proposed theory in the model. For instance, the action of the inhibitory control of automatic responses allows conscious control of the behavioral response to situations faced by human beings. Therefore, the action of correcting an error would largely depend on this control as it is necessary to stop the automatic response that makes the subject persevere and repeat a mistake [41].

The role of cognitive and behavioral regulation using internal language allows subjects to keep the governing rules of their behavior in mind, allowing them to guide each of the actions they perform, which is critical when correcting an error [42]. If the subjects do not have the linguistic content that describes the problem-solving steps, they will make the mistake again [43, 44]. The regulation of the limbic system allows for the conscious control of the emotional response to situations faced by individuals in their daily lives. In the case of error correction, there should be an adequate emotional reaction enabling the subjects to behave in favor of learning from the negative experience and correcting it. Otherwise, an excessive and equivocal emotional reaction would cause the subjects not to act correctly or correct their mistakes [45, 46].

Decision-making is a critical variable in this proposed cognitive mechanism. To correct an error, it is necessary to activate the ability to decide correctly and consider the positive and negative consequences of the choice. In this way, individuals can project themselves properly and avoid repeatedly falling into an error [47-49]. Verification is an executive function allowing individuals to assess the result of their action once completed. In the case of error correction, verification plays an important role, as the subjects must evaluate whether their conduct allows them to correct an error or not. Therefore, verification must be active in the error correction mechanism to ensure that subjects do not repeat a mistake [28]. For example, similar to the relationships proposed in our model, the difficulty in impulse control was related to difficulties for adequate executive functioning [50]. Additionally, there was an interactive dynamic between executive functions, such as inhibitory control, cognitive flexibility, and regulatory internal language of behavior, allowing the subjects to express adequate behaviors within adequate parameters [51-52]; that is, correcting the errors that it presents. The findings described in this article are also in line with previous studies that indicated deficits in some of the executive functions described in our model could lead to behavior without error correction, such as in the case of people who suffer from addictions, manifest violent behaviors [53, 54], encounter educational failure, and experience eating disorders [55], among other others.

Regarding the hypotheses raised, the data provided significant empirical evidence. The statistical analysis showed that the regressions performed were significant, and the model had, in general, adequate goodness of fit. Consequently, the findings in this research are projected as a further contribution to understanding the error correction process and navigating the complexity of the study of executive functions. The theoretical model proposed in this article contributes to different areas. In the clinical context, it provides greater clarity concerning the subcomponents existing before the correction of an error. This opens the way for neuropsychological treatment processes, whereby actions focus on stimulating the described executive functions within the rehabilitation process for those with frontal damage who have difficulties at this level [56-58]. From the theoretical perspective, this study presents a significant contribution, given that the body of research on executive functions is still developing in terms of its theoretical models [3]. However, this study found the ability to correct errors as a highly complex executive function that could be understood through an interactive mechanism.

The subjective nature of the self-report instruments applied to measure executive functions must be declared. Although the research sample was obtained randomly, the participants belonged to a specific city, which limits the generalizability of the results. However, the framework used in this research may be similarly applicable to other social contexts, enabling researchers to understand the error correction processes of their citizens. Another factor that needs analysis in the tested model is the cultural characteristics that may influence its configuration [59]. Therefore, it is necessary to test the model in other contexts to determine whether the paths found are significant in different social dynamics or not.

5- Conclusion

According to the results of this research, the ability to correct human errors is the product of the interaction of various executive functions. The adequate statistical fitness of the proposed model allowed us to conclude that the suggested dynamics largely explained the error-correction process. The main contribution of the research lies in understanding that certain executive functions, such as internal language regulating behavior and cognition, the inhibitory control of automatic responses, the regulation of the limbic system, decision-making, and cognitive and behavioral verification, work collectively to correct a mistake. This proposal significantly contributes to the theoretical construction of executive functions. In addition, in a clinical sense, the identification of various brain functions that should undergo intervention in neuropsychological treatment.

One plan is to carry out future research on error correction that includes a greater number of participants in Latin America. In addition, future projects include the testing of the model in different contexts where the ability to correct errors is crucial to success. Such as in clinical settings with individuals experiencing frontal brain damage, educational contexts with students showing low academic performance, professional settings with workers suffering from behavioral difficulties, those deprived of liberty, and other settings of interest in the context of neuropsychology.

6- Declarations

6-1- Author Contributions

C.R-G. contributed to the conceptualization, investigated the data, carried out the formal analysis and project administration, wrote the original draft, and reviewed and edited the manuscript. J.C-C. investigated the data, carried out the formal analysis, and reviewed and edited the manuscript. V.R. investigated the data, wrote the original draft and carried out the formal analysis. All authors have read and agreed to the published version of the manuscript.

6-2- Data Availability Statement

The data that support the findings of this study are available upon request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

6-3- Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6-4- Ethical Approval

This research was approved by Comité de Ética para la Investigación con Seres Humanos, Universidad Tecnológica Indoamérica.

6-5- Informed Consent Statement

All participants provided their written consent to participate in this study.

6-6- Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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Appendix I

Table A1. Executive Functions Scale

Factor	Items
Decision Making	DM1 Make decisions, considering the implications that may result. DM2 Make decisions without difficulty, even in the face of the simplest things. DM3 Possess the ability to make decisions independently.
Verification of cognitive and behavioral activity	V1 Check the spelling and writing of your messages before sending them. V2 At the end of a meeting, verify that your behavior was appropriate. V3 When you do an evaluation, check that you have answered all the questions before submitting it.
Error Correction	EC1 Correct the mistakes caused by your behavior. EC2 When you carry out an activity, you can correct the errors that take you away from the proposed objective. EC3 When you make a mistake due to the way you act in front of the people around you, you seek to solve it.
Inhibitory Control of Automatic Responses	IC1 Think before saying things to other people. IC2 Allow others to speak without interrupting. IC3 Reflecting before acting and not doing the first thing that passes through your mind. IC4 Awareness of the effects your behavior has on other people.
Internal Language Regulator of Behavior and Cognition	L1 Inner voice that guides your actions L2 When faced with a task, your internal voice tells you what you must do to achieve it successfully. L3 When you have made a mistake, your inner voice guides you to correct your mistake.
Regulation of the Limbic System	LS1 When angry, you are able to calm down easily. LS2 Manage to react calmly to different situations. LS3 Ability to control anger reactions.