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Translators' Allocation of Cognitive Resources in Two Translation Directions: A Study Using Eye-Tracking and Keystroke Logging

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Abstract: This study investigates how novice translators distribute their cognitive resources during translation between English and Chinese in both directions, with particular attention paid to the role of translation direction and the divergence between empirical findings and participants' introspective reports. A combination of eye-tracking and keystroke logging was used to quantify cognitive effort, incorporating participant variation, attention unit type (ST, TT, parallel), gaze event duration, and average pupil dilation. A Generalized Linear Model (GLM) was applied, with average pupil dilation as the response variable and gaze event duration, AU type, and participant as covariates. An interaction term between gaze event duration and AU type was included in the E-C GLM but omitted from the C-E GLM due to non-significance. The results reveal distinct cognitive demands across translation directions. In English–Chinese (E-C) translation, ST processing significantly reduces pupil dilation (by 3.56%, $p < 0.001$), whereas TT processing leads to increased cognitive load, particularly during prolonged fixations, with pupil dilation increasing by 1.4% ($p = 0.033$). In Chinese–English (C-E) translation, ST processing does not significantly differ from parallel processing ($p = 0.285$), and TT processing reduces pupil dilation by 4.75% ($p < 0.001$), suggesting that it involves a lower cognitive effort than E-C translation. Gaze event duration significantly affects pupil dilation in C-E translation ($p < 0.001$); however, its influence in E-C translation varies according to the types of cognitive processing involved. Moreover, a significant gap is observed between the participants' self-reported reflections and the quantitative data, a disparity that is strongly shaped by the direction of translation. These findings contribute to a deeper understanding of cognitive effort in translation and raise implications for translator training, assessment, and cognitive translation studies, particularly in contexts where translation direction and processing mode interact to shape cognitive demand.

Keywords: translators; eye-tracking; keystroke logging; cognitive resources; translation direction; self-reflection

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1. Introduction

The concept of translation directionality—whether translation occurs from a second language into the translator's native language (L1) or vice versa—has been a longstanding and central focus in translation studies [1–5]. Researchers have examined this topic through multiple lenses, such as 'inward' versus 'outward' translation practices, differences across regions and nations, and the impact of political, economic, and sociocultural contexts [3] (p. 898). Despite these advancements, a crucial question remains unanswered: does translation directionality influence the allocation of cognitive resources, and if so, how?

While previous studies have utilized eye-tracking to examine cognitive load in written translation [1–4], conference interpretation [2,6], simultaneous interpretation [7–12], translation competence [5,6], and translator training [8] between L1 and L2 translations [10], the findings remain inconsistent and often inconclusive. A key shortcoming in existing research is the limited attention given to the alignment—or lack thereof—between objective, data-driven indicators (such as those captured through eye-tracking and keystroke logging) and translators' introspective accounts of their own mental processes. This disconnect obscures a fuller understanding of how cognitive resources are allocated in real time and how translators perceive their own mental effort during the task.

To address this gap, the present study adopts an integrative methodology combining eye-tracking and keystroke logging techniques to investigate cognitive resource distribution among novice translators working in both English-to-Chinese and Chinese-to-English directions. The research focuses on the role that translation direction plays in shaping mental effort and aims to examine how observed behavior aligns—or contrasts—with participants' self-assessments. Cognitive effort in this study is quantified using four core indicators, developed by Hvelplund [12]: Total Attentional Duration (TA duration), AU count, AU duration, and pupil dilation. These measures offer a multifaceted view of how translators attend to the source text (ST), produce the target text (TT), or engage in both actions simultaneously. We aim to test the following three primary hypotheses:

(1) Translators engage in overlapping processing of the source text (ST) and target texts (TT) in both translation directions.
(2) Translators allocate more cognitive resources to TT processing than to ST processing or simultaneous (parallel) processing in both translation directions.
(3) Translators may underestimate the cognitive resources devoted to first-language production during L2-L1 translation.

To test these hypotheses, data were collected from 24 Chinese translator trainees and analyzed use Generalized Linear Models (GLMs) to assess the relationship between directionally and cognitive effort. By combining behavioral data with retrospective self-reflection, this research seeks to provide a more nuanced perspective on how cognitive processes function during translation. It aims to refine theoretical models and offer practical implications for translator training and assessment, especially in relation to translation directionality and the mental demands it entails.

2. Theoretical and Methodological Considerations

2.1. Processing Types and Allocation of Cognitive Resources in Translators

Translation engages multiple layers of cognitive effort, involving both intentional focus and more automatic mental functions. Scholars have approached the division and description of these resources in various ways. Translation researchers have described these cognitive demands in various ways. Traditionally, the translation workflow has been categorized into two main phases, comprehending the source text (ST) and generating the target text (TT), e.g., [12–14]. Recent theoretical and empirical developments, however, have introduced a third dimension, "parallel processing", highlighting how translators often switch between or simultaneously handle ST understanding and TT formulation [15–18].

Insights from neurolinguistics and cognitive psychology suggest that multitasking is fundamental to how translation unfolds. Rather than progressing linearly from reading to writing, translators frequently adopt overlapping strategies, integrating comprehension and production [19–21]. Evidence from keystroke logging and eye-tracking studies reinforces this view, showing that there is frequent simultaneous attention to both ST and TT, challenging linear models of the translation process [6,22–26].

To better capture this complexity, Hvelplund [12] introduced the concept of attention units (AUs), mapping this activity more precisely. These include (1) ST AUs—focused on interpreting the source material; (2) TT AUs—concerned with constructing the translation; and (3) parallel AUs—capturing moments when both tasks occur concurrently. These distinctions have enabled more precise measurements of attention distribution and cognitive effort during translation.

Building on this framework, the present study employs four empirical indicators—Total Attentional Duration, AU count, AU duration, and pupil dilation—to quantify cognitive effort for different translation directions and processing types. By adopting Hvelplund's AU categorization, we aim to capture the dynamic nature of attention allocation in translation and provide deeper insights into how cognitive resources are managed during ST comprehension, TT production, and their concurrent execution.

2.2. *Defining Cognitive Units in the Translation Process*

To capture the way translators allocate cognitive resources, the concepts of translation unit (TUs) and attention units (AUs) have been proposed to quantify continuous cognitive processing over time. Originally defined in linguistics as the smallest meaningful segment in a translation [27–36], the translation unit (TU) has evolved within cognitive translation studies to represent cognitive processing effort. Specifically, it denotes the focus of attention during translation [28], encapsulating the segment that is actively processed [12] and serving as a key unit of cognitive activity [29] (p. 953). This expanded definition integrates real-time keystroke and eye-tracking data, enabling a detailed analysis of cognitive resource allocation during translation [28].

Carl and Kay [34] describe AUs as segments of text that attract a translator's attention at any given moment. Their research suggests that AU boundaries shift depending on cognitive demands and translator experience. Hvelplund [12] formalized these observations by identifying three AU types: ST (comprehension), TT (production), and parallel (combined). This study adopts Hvelplund's AU framework to measure real-time cognitive effort across ST, TT, and parallel processing [12] (p. 116). These units provide a precise means of evaluating cognitive allocation patterns, enhancing models of translation as a cognitively regulated process. To achieve this, we categorize our data into four groups—Group A, Group B, Group C and Group D—based on the distinct macro- and micro-AU classifications of Hvelplund [12], as presented in Table 1.

Table 1. Macro- and micro-AU classifications used in this study.

AUs Classification	Macro AUs	Micro AUs	Details
Group A	ST AU (Source Text Attention Unit)	ST Gaze	Corresponds to ST comprehension; includes eye gaze on ST and typing without gaze.
Group B	TT AU (Target Text Attention Unit)	Gaze Off + Typing No Gaze + Typing TT Gaze + Typing TT Gaze	Corresponds to TT production; includes gaze on TT and typing activity.
Group C	Parallel AU	ST Gaze + Typing	Reflects simultaneous ST and TT processing.
Group D	No data	Gaze Off	Inactive moments, pauses, or unclassified activities.

2.3. Empirical Approaches to Modeling the Translation Process

Eye-tracking technologies allow for the precise observation of how translators read and allocate attention, providing valuable temporal and spatial data. While these tools are highly effective, they still face methodological limitations, particularly in distinguishing between early comprehension and deeper interpretive phases. The boundary between understanding and production can also become blurred in authentic translation settings [31] (p. 129). Nonetheless, the combined use of eye-tracking and keystroke logging has emerged as one of the most efficient methods for investigating cognitive processes in translation.

Several empirical models have been developed to account for the complexities of translation cognition. Tirkkonen-Condit [37] proposed that literal translation serves as a default strategy until a problem is detected, which then triggers a shift to conscious decision-making [31] (pp. 407–408). Building on this, Schaeffer et al. [38] suggested that translators initially form provisional representations that mirror the source text's structure and meaning, adjusting these only when contextual or linguistic constraints intervene.

Alves and Vale [33], drawing on Relevance Theory [39–41], introduced a dual-mode model comprising a stimulus mode (s-mode) and an interpretive mode (i-mode), which are thought to unfold along distinct cognitive timelines [33] (p. 256). Carl [31] expanded on this framework through the Monitor Model, which conceptualizes translation as a process driven by both automatized priming routines and higher-order monitoring strategies. Translation, according to this model, progresses in translation units, with oversight mechanisms regulating the degree of interlingual similarity based on task-specific goals, stylistic norms, or quality expectations [19] (p. 257). Moreover, this Monitor Model emphasizes the interplay between horizontal (within-level) and vertical (cross-level) monitoring processes, as outlined by De Groot [27]. This theoretical framework is particularly relevant to our study, as it offers a robust basis for analyzing cognitive effort using eye-tracking and keylogging. It provides a nuanced lens through which to understand the coordination of automatic and controlled processes, especially in relation to variations in cognitive demand across translation directions.

2.4. Cognitive Resource Allocation Across Translation Directions

The role of translation direction—whether from L2 to L1 or vice versa—has been investigated across various dimensions, including metaphor processing [3], translation accuracy [3,39–42] and cognitive load [17,43–45]. For example, Chang [42] utilized eye-tracking and fMRI to evaluate whether cognitive asymmetries found at the word level persist in full-text translation. His findings supported the views of the Revised Hierarchical Model. Expanding on this work, Wang [3] investigated how directionality influences metaphor translation and attention distribution. Later, Wang et al. [17] examined the differential cognitive demands of automatic versus controlled processing and found that translation into L2 required greater attentional resources. Interestingly, translations from L2 into L1 were often more accurate, likely due to greater familiarity with the target language's structure.

While such studies have yielded valuable insights, they tend to underrepresent translators' subjective experiences and self-perceptions of cognitive load. To address this gap, we adopt a multimethod design that integrates eye-tracking, keystroke logging, and retrospective self-reflection. Keystroke logging captures behavioral indicators of cognitive effort, including typing speed, revision patterns, and pauses during target text (TT) production. In parallel, participants' introspective accounts provide qualitative insights into their perceived mental workload. This triangulated methodology enables a more comprehensive analysis of cognitive resource allocation in translation. Specifically, our study aims to examine (1) how attention is distributed between source text (ST) comprehension and target text (TT) production; (2) variations in attentional metrics such as total attentional (TA) duration, AU count, and pupil dilation; and (3) the extent to which introspective reflections align with empirical data. By bridging objective measurement and subjective experience, this study contributes to a more nuanced understanding of how translation directionality shapes cognitive demand.

3. Materials and Research Design

3.1. Participants

The study involved 24 postgraduate students enrolled in translation studies programs at various UK universities. All participants were native speakers of Chinese (L1) and used English as their second language (L2), with IELTS scores of 7.0 or above, ensuring a consistent level of English proficiency. They reported prior experience with computer-assisted translation tools and had previously taken part in experiments utilizing eye-tracking, keystroke logging, and cue-based Retrospective Think-Aloud Protocols (RTA), which contributed to the smooth implementation of the current research.

The decision to recruit only native Chinese speakers was based on our research focus: examining cognitive effort allocation in different translation directions (L1 → L2 and L2 → L1) among novice translators with a shared linguistic background. This design helps reduce variability stemming from differences in language proficiency, translation training, or linguistic typology. Including a mixed population of native English and native Chinese translators could introduce confounding factors, potentially obscuring the results. While we acknowledge that a cross-linguistic comparison between native English and native Chinese translators would provide additional insights, such an approach falls beyond the scope of this study and is highlighted as a future research direction.

Although the sample size of 24 participants may appear limited, our study adopts a within-subject design, where each participant performed multiple translation tasks. This approach resulted in a substantial dataset of eye-tracking and keystroke-logging records and enhanced statistical power by allowing for direct comparison across conditions within the same individuals, thereby reducing the variability that can arise in a between-subject design.

To ensure the adequacy of our sample size, we conducted a post hoc power analysis using G*Power 3.1.9.7 (statistical power analysis to compute effect sizes), based on effect sizes observed in previous eye-tracking studies on cognitive translation processing (e.g., [1,12]). The analysis focused on detecting differences in Total Attentional Duration (TA duration), AU count, AU duration, and pupil dilation across translation directions. The power analysis yielded the following results:

Effect size (Cohen's f^2) = 0.35 (large effect, based on prior research estimates);

Alpha level = 0.05;

Power ($1-\beta$) = 0.85;

Required minimum sample = 19 participants (for within-subject comparisons).

Since our sample size (N = 24) exceeds the minimum required for detecting statistically significant effects at a power level of 0.85, we are confident that our dataset is sufficient for drawing meaningful conclusions.

Prior to participation, all individuals provided informed consent, in accordance with established ethical research guidelines. Data from twenty-one participants met the inclusion criteria for analysis. These criteria were based on established benchmarks and included (1) the total gaze duration on the screen, (2) the proportion of gaze samples successfully classified as fixations, and (3) the average fixation duration. We followed the standards proposed by Rayner [43] and Hvelplund [12].

3.2. Materials

The source texts used in this study comprised simulated dialogs situated within a business context, depicting interactions between Chinese and British speakers. These dialogs were displayed onscreen and deliberately constructed to align with the study's research parameters. Both the English and Chinese texts were informal, conversational in tone, and free from poetic elements, complex sentence structures, or specialized terminology. The aim was to mirror authentic professional communication, thereby enhancing the relevance of the materials for translation tasks in business environments.

The English text consisted of 125 words, while the Chinese version contained 151 words, with both comprising 9 sentences, labeled S1–S9 for analytical consistency. Each sentence was rigorously evaluated and aligned at multiple linguistic levels—including syllables, words, and sentence structures—to ensure cross-linguistic equivalence. Alignment criteria included word count, stylistic features, genre, sentence type and structure, sentence length, word frequency, lexical difficulty, and character or word length.

This meticulous standardization of linguistic and contextual variables ensured equivalency between the two texts, thereby supporting valid comparisons in cognitive resource allocation during translation. Additionally, the simulated healthcare dialog incorporated into the design enhances the study's applicability, particularly in translation scenarios relevant to medical and professional interpretation contexts.

3.3. Experimental Procedure

The entire experimental session lasted for approximately 35–40 min per participant, depending on task completion speed (see Figure 1—workflow flowchart).

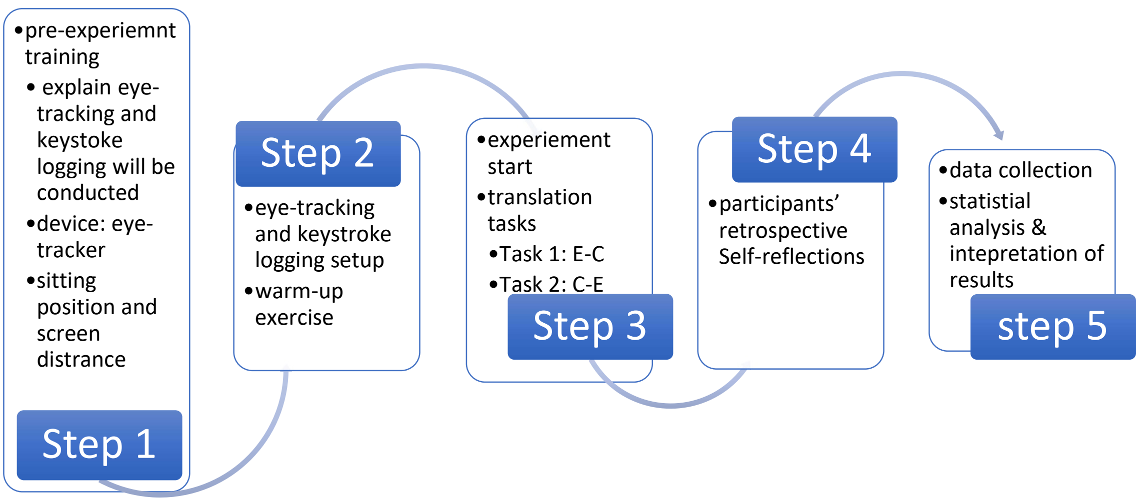

Figure 1. Step-by-step workflow of the experimental procedure.

Step 1: Before commencing with the main experiment, participants completed a preliminary training session designed to acquaint them with the experimental setup and procedures. During this session, they were given instructions on how to use the tools and were provided with examples of the tasks to ensure understanding. Participants were asked to seat at a distance of 60–65 cm from the screen throughout the session and the Tobii TX300 (Tobii Technology AB, Stockholm, Sweden) remote eye tracker was set up, allowing calibration for each participant to ensure the accurate recording of eye movements.

Step 2: Participants completed two sets of 50-word translation tasks, one translating from English to Chinese and the other from Chinese to English, as a warm-up exercise. This was performed to ensure participants' comfort and consistency in their use of the equipment.

Step 3: Participants began their translation tasks, during which their eye movements and keystroke logging data were recorded.

Step 4: Follow-up participants' retrospective self-reflections.

Step 5: Data collection and statistical analysis. To analyze the collected data, a Generalized Linear Model was employed, considering relevant co-variables. For the English-to-Chinese (E-C) dataset, variables included the size of the Area of Interest (AOI) for eye fixations, word frequency, average syllables per word, and the average number of letters per word. In the Chinese-to-English (C-E) models, AOI size and word frequency were used as key predictors. These linguistic variables were selected based on widely recognized readability metrics, such as the Flesch Reading Ease, Gunning Fog Index, Flesch–Kincaid Grade Level, Coleman–Liau Index, SMOG Index, Automated Readability Index, and Linsear Write Formula. Core factors evaluated included sentence count, average sentence length (in characters, aligned with AOI size), syllabic complexity, the proportion of complex words, and character length per word.

This carefully structured analytical approach enhances the reliability and validity of the findings, supporting the study's objective to investigate how cognitive resources are allocated during translation tasks.

4. Results and Discussions

4.1. Eye Tracking and Keystroke Logging Data Analysis

Table 2 provides a detailed description of the 10 categorical and continuous variables collected throughout the experiment in both English-to-Chinese (E-C) and Chinese-to-English (C-E) translation directions. These variables were recorded using eye-tracking and keystroke logging technology, capturing key metrics related to fixations, gaze behavior, and pupil dilation.

Table 2. Description of variables collected during experimental process.

Variable	Description	Comment	Categories
FixationIndex	Unique ID for fixation	[1:936]	-
Participant	Unique ID for participant	Factor with 18 levels	P01, P02, P03, P04, P05, P08, P09, P10, P11, P12, P13, P14, P16, P17, P18, P19, P20, P22
AU_type	The task which is currently being performed	Factor with 3 levels	1: parallel, 2: source text (ST), 3: target text (TT)
FixationPointY (MCSpx)	Point on the screen of gaze along the y-axis	[0:900]	-
GazeEventDuration	The amount of time spent gazing at a single point, recorded in (ms)	[0:9500]	-
KeyDefinition	The label generated by the eye tracking software	This takes the form of a string	-
FixationPointX (MCSpx)	Point on the screen of gaze along the x-axis	[0:1400]	-
PupilLeft	The dilation of the left eye pupil	Continuous	-
PupilRight	The dilation of the right eye pupil	Continuous	-
AVGpupildillation	The average pupil dilation of both pupils	Continuous	-

The dataset includes categorical variables such as participant ID, which identifies individual participants, and AU_type, which specifies the translation task being performed (parallel, source text (ST), or Target Text (TT)). Additionally, the dataset contains continuous variables related to gaze behavior, including FixationPointX and FixationPointY (screen coordinates of gaze), GazeEventDuration (time spent fixating on a point in milliseconds), and pupil dilation measures (PupilLeft, PupilRight, and their average, AVGpupildilation).

Table 3 presents summary statistics for average pupil dilation in both English-to-Chinese (E-C) and Chinese-to-English (C-E) translation directions. Pupil dilation values were obtained by averaging left and right eye pupil measurements, providing a single measure of cognitive effort. The results indicate that the median pupil dilation is slightly lower in C-E translation (2.799) compared to E-C translation (2.853), suggesting potential differences in cognitive load between translation directions.

Table 3. Summary of statistics for average pupil dilation.

English-to-Chinese (E-C) Translation Direction						
Variable	Min	1st Qu.	Median	Mean	3rd Qu.	Max
PupilLeft	1.690	2.658	2.885	2.853	3.012	3.912
PupilRight	1.466	2.645	2.811	2.852	3.043	4.197
AVGpupildillation	1.812	2.655	2.853	2.853	3.029	4.033
Chinese to English (C-E) Translation Direction						
Variable	Min	1st Qu.	Median	Mean	3rd Qu.	Max
PupilLeft	1.800	2.606	2.827	2.817	3.004	4.000
PupilRight	1.899	2.594	2.773	2.838	3.072	4.184
AVGpupildillation	1.927	2.602	2.799	2.828	3.032	4.090

To visualize the distribution of pupil dilation, Figure 2 displays histograms for both translation directions. The distributions exhibit a slight right skew, with a peak around 3.0. This suggests that most pupil dilation values fall within a central range, with higher dilation values appearing less frequently. Instances of elevated pupil dilation may indicate moments of increased cognitive load, potentially due to difficult translation segments or higher processing demands. The presence of extreme dilation values further supports the idea that certain translation tasks induce cognitive overload, requiring increased attentional resources.

The boxplots in Figures 3 and 4 provide a broad overview of participant variation in cognitive effort across both English-to-Chinese (E-C) and Chinese-to-English (C-E) translation directions, without distinguishing between AU types. In each boxplot, the dots represent individual data points that fall outside the interquartile range (IQR), indicated by the box, and are referred to as outliers. These points highlight instances where measurements such as pupil dilation or gaze event duration notably deviate from the median (marked by the horizontal line within each box), reflecting moments of particularly elevated or reduced cognitive load during translation tasks. Figure 3 illustrates overall pupil dilation per participant, while Figure 4 presents gaze event duration across participants, capturing fixation behavior during translation tasks. In Figure 3, some participants, such as P01 and P09, exhibit consistently higher median pupil dilation, whereas others, such as P18, show lower median pupil dilation. These variations may reflect differences in cognitive load, translation expertise, or individual processing strategies. The presence of numerous outliers in both translation directions suggests that certain translation segments required significantly greater cognitive effort, potentially due to challenging lexical choices, ambiguous structures, or increased decision-making demands. Similarly, Figure 4 highlights variation in gaze event duration across participants, providing insights into fixation behavior during translation. Some participants, such as P10 and P20, display longer gaze event durations, indicating that they spend more time fixating on specific areas before making translation decisions. Conversely, others exhibit shorter fixation durations, suggesting a more rapid or fluent translation approach. The large variance in fixation durations suggests that some participants engage in frequent, shorter fixations, while others rely on longer fixations to process information.

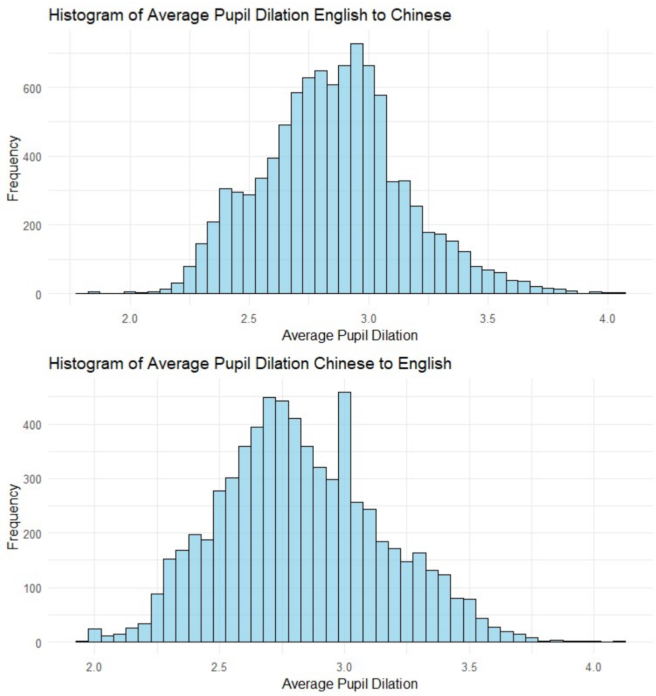

Figure 2. Histogram of average pupil dilation.

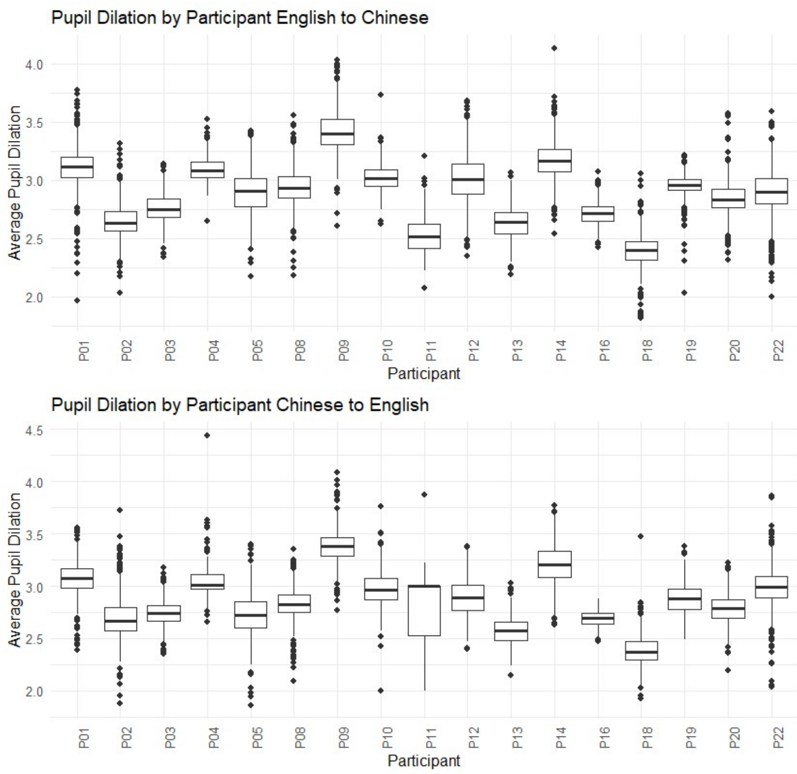

Figure 3. Pupil dilation by participant.

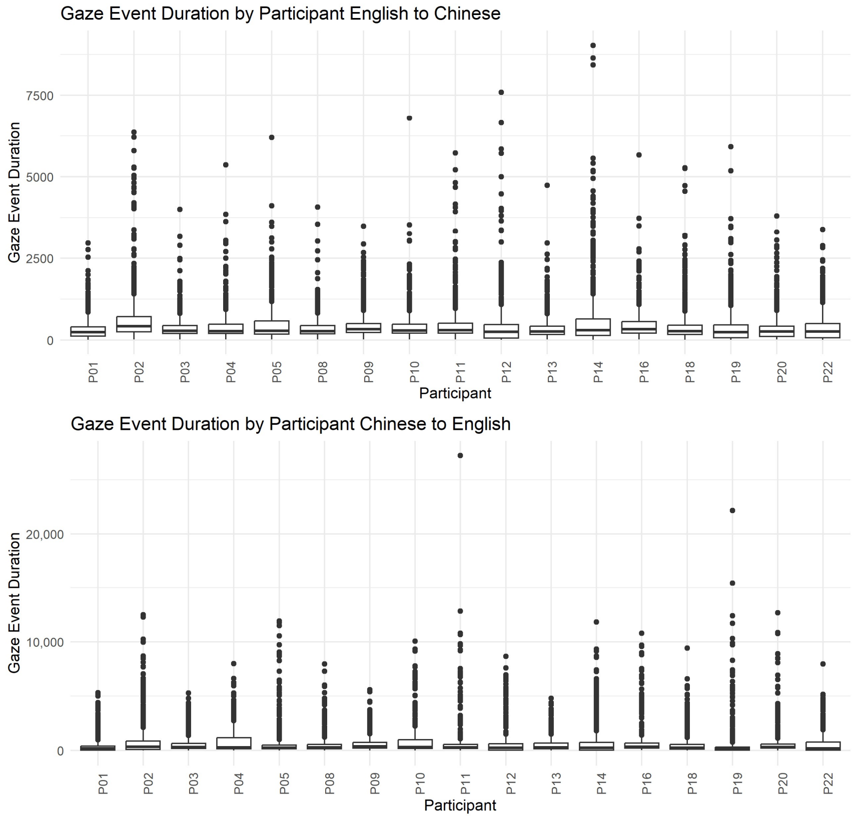

Figure 4. Gaze event duration by participant.

Figure 5 presents boxplots of pupil dilation across AU types (parallel, ST, and TT) for both translation directions (E-C and C-E), highlighting differences in cognitive effort across translation tasks. The results indicate that TT processing exhibits a slightly higher median pupil dilation than ST and parallel processing, suggesting that text production (TT) demands greater cognitive effort than comprehension (ST). In both translation directions, ST processing has a slightly lower median pupil dilation than parallel processing, aligning with the expectation that comprehension (ST) is less cognitively demanding than multitasking (parallel). The spread of dilation values appears consistent across AU types, indicating that cognitive effort varies within each condition but follows a similar distribution. The presence of outliers above 3.5 suggests that some translation segments elicited substantially higher cognitive load, potentially due to increased difficulty, ambiguous sentence structures, or complex lexical choices. Figure 6 displays the distribution of gaze event duration across AU types for both translation directions, offering insights into how visual attention is allocated during different translation tasks. The results show that TT processing has the longest median gaze event duration, reinforcing the idea that text production requires prolonged fixations, likely due to increased cognitive demands. In contrast, ST processing exhibits the shortest gaze durations, suggesting that comprehension is a more fluid process that requires less sustained attention. Parallel processing falls between ST and TT, indicating that multitasking demands more visual attention than ST but less than TT. The presence of substantial outliers in TT processing, with some gaze durations exceeding 6000 ms (E-C) and 20,000 ms (C-E), suggests that certain translation segments require significantly more cognitive effort, possibly due to lexical retrieval challenges, decision-making processes, or syntactic complexity. These findings also support the necessity of including an interaction term between gaze event duration and AU type in the statistical models. Given that gaze event duration appears to influence pupil dilation differently depending on the processing condition, failing to model this interaction could overlook important cognitive differences between ST, TT, and parallel processing across translation directions. By incorporating this interaction into our analysis, we can gain deeper insights into how translation processing types modulate the relationship between fixation duration and cognitive load, further refining our understanding of cognitive effort in bilingual translation tasks.

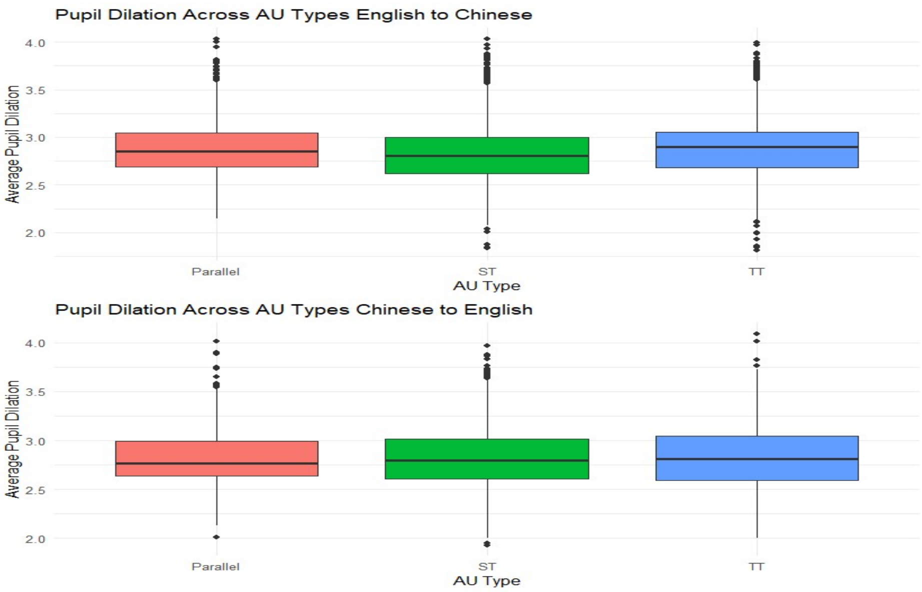

Figure 5. Average pupil dilation across AU_type.

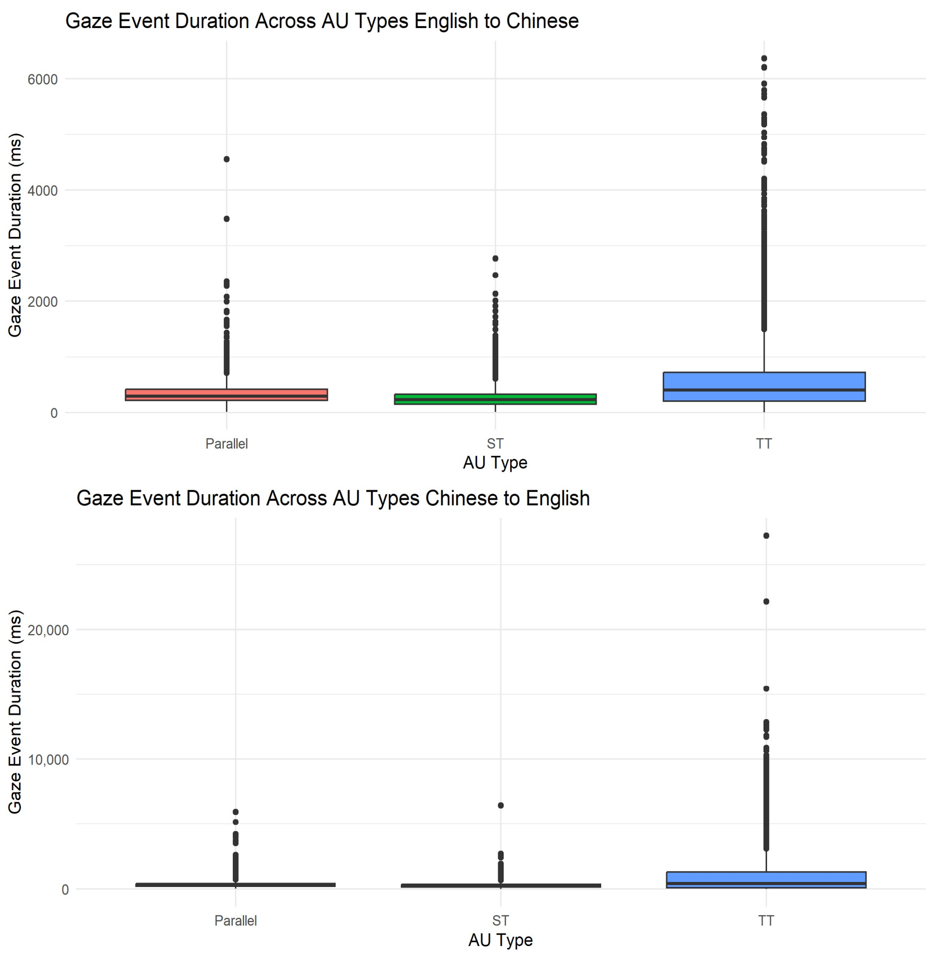

Figure 6. Gaze event duration across AU_type.

Figure 7 illustrates the relationship between pupil dilation and gaze event duration for both English-to-Chinese (E-C) and Chinese-to-English (C-E) translation directions. The blue curve in each scatterplot represents a smoothed trend line, obtained using a locally weighted regression (LOESS),indicates a weak overall relationship, with minimal variation in pupil dilation across gaze durations. In the E-C direction, pupil dilation remains largely stable, suggesting that longer fixations do not significantly impact the cognitive load. In contrast, the C-E direction shows a slight increase in pupil dilation for shorter fixations (~250 ms), followed by a decline for longer durations (~750+ ms). This may indicate higher cognitive effort during initial fixations, followed by adaptation over prolonged gazes. Most fixations are brief (<250 ms), with greater variability at longer durations, particularly in the C-E condition, suggesting increased cognitive demand in specific translation segments. These findings highlight the importance of modeling the interaction between gaze event duration and AU type, as cognitive load appears to vary by translation direction and fixation length.

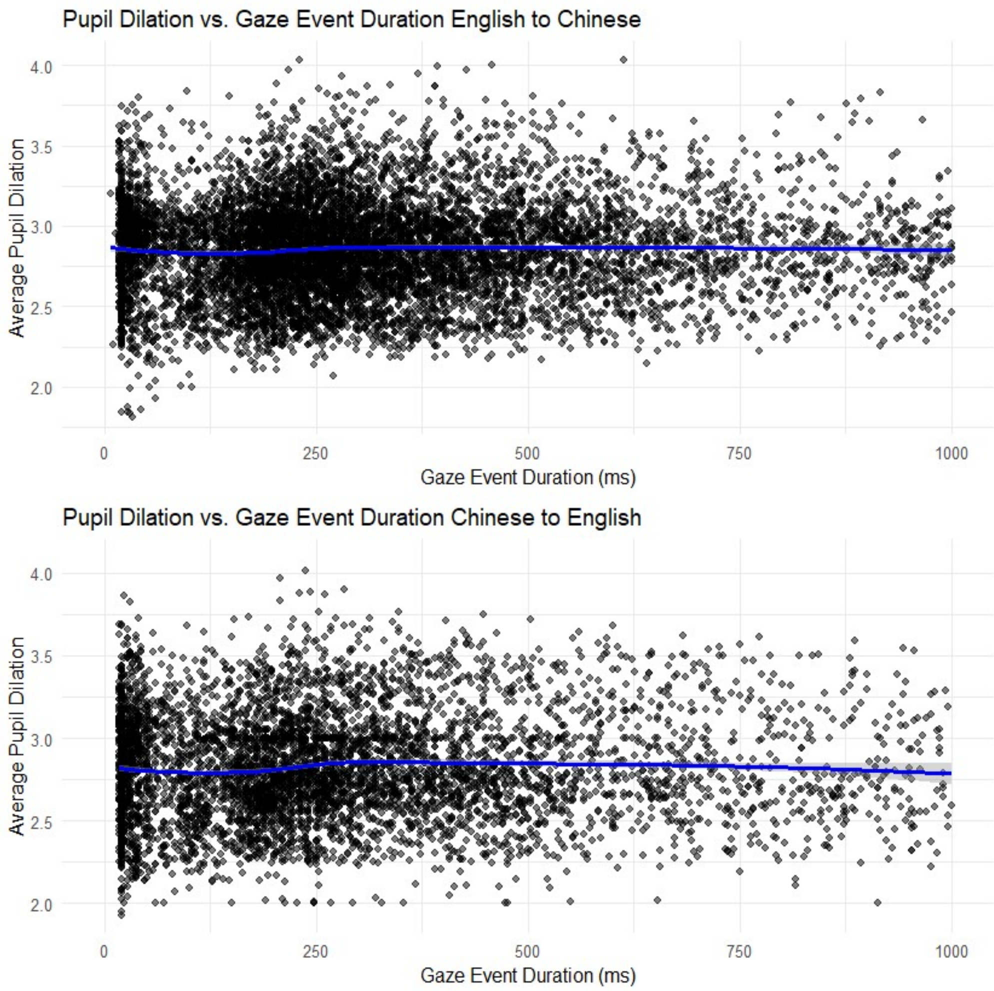

Figure 7. The relationship between pupil dilation and gaze event duration.

We now proceed to visualize gaze event duration. As an example, we illustrate through Figure 8 the cognitive processing throughout Participant 13's complete English–Chinese translation task. The horizontal axis represents a typing event, and the vertical axis represents duration of eye gaze for that event, also known as AU. TT (red) dominates throughout, indicating the translator's sustained cognitive efforts directed predominantly toward text production. Longer-duration fixations (higher bars) in TT segments suggest points of greater cognitive difficulty or decision-making complexity in target text production. Parallel processing (green bars) appears frequently, showing the translator often simultaneously comprehends the source text and produces the target text. Frequent occurrences of parallel processing indicate moments when the translator actively integrates the comprehension of the source text with simultaneous text production. This aligns clearly with prior studies suggesting that translation often involves parallel cognitive effort as in Hvelplund [12]. ST processing (blue bars) occurs more frequently, but with a shorter duration, suggesting that the translator reads whole sentences to completion before starting their translation task. This aligns with Carl and Dragsted's [29] findings on parallel processing, where translators gather information from the ST while producing the TT.

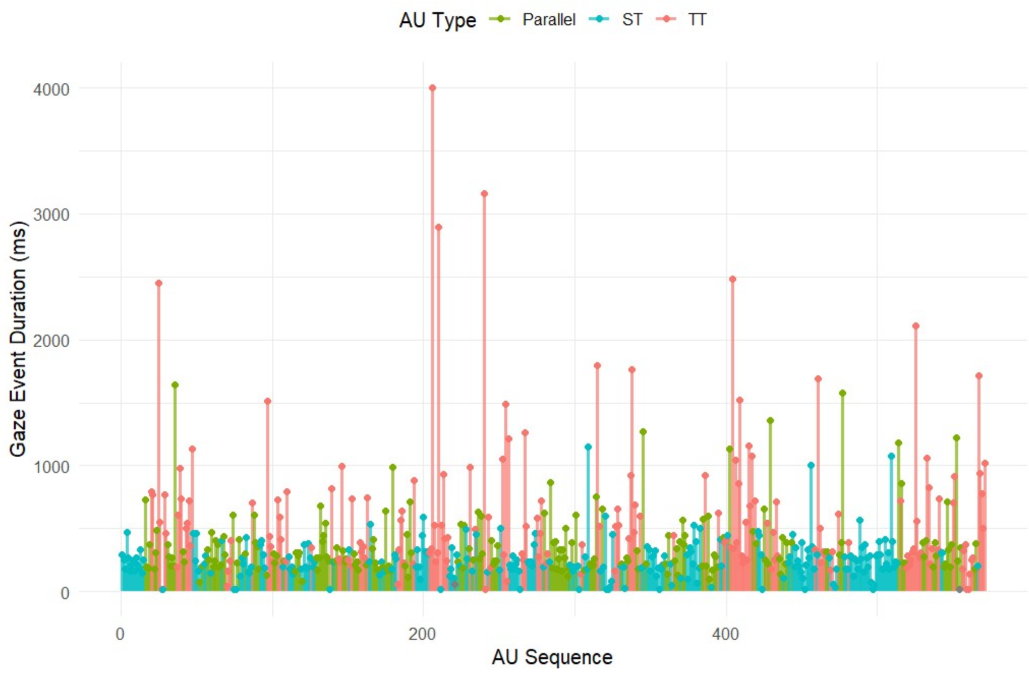

Figure 8. Timeline of attention units for the entire experiment for Participant 13: English–Chinese Translation. Parallel is displayed in green, source text (ST) in light blue, and target text (TT) in red. Each AU sequence has not been labeled for reliability.

To interpret and make sense of what is going on during the translation, we display the first 75 events of for Participant 13 in Figure 9. Early in the translation task (AU 1–20), Participant 13 mainly engaged with ST comprehension (blue bars). This clearly indicates an initial orientation phase, dedicated primarily to un-derstanding source content before typing. After initial comprehension, TT (red) and Parallel (green) processing clearly dominate, demonstrating frequent simultaneous comprehension-production activities. Clear instances of parallel processing highlight ongoing engagement with the source text even during active typing activities, reflecting cognitive multitasking during translation. Pronounced peaks such as "BackYOU" around AU 30 and indicate heightened cognitive effort possibly due to complex linguistic decisions, in particular on self-correction or during translation. The annotations like "Return", "Space", and specific characters provide evidence of active typing and editing processes, clearly linking cognitive activities (gaze duration) to concrete keystroke events.

Parallel coordination of ST comprehension and TT production was frequently observed. Keystroke logging activity often overlapped with eye fixations on the ST, indicating concurrent comprehension and production processes. Keystroke logging activity itself is evidence of cognitive effort in TT production, as participants explicitly reported ST comprehension while typing, corroborated by eye-tracking data.

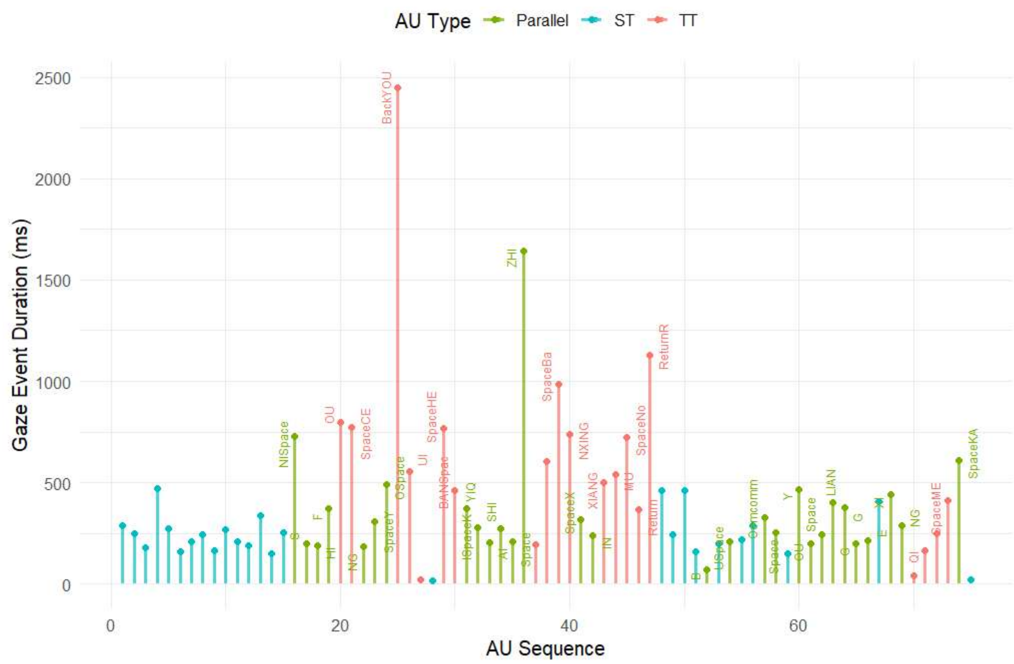

Figure 9. A timeline of attention units for the first 75 events for Participant 13: English–Chinese Translation. Parallel is displayed in Green, Source Text (ST) in Light Blue, and Target Text (TT) in Red. Each AU is labeled.

4.2. Building a Generalized Linear Model to Assess the Difficulty of E-C and C-E Translation Tasks

To analyze average pupil dilation (AVGpupildilation) in English-to-Chinese (E-C) translation, we employed Generalized Linear Models (GLMs) to examine the effects of AU_type (attention unit type: ST, TT, parallel [reference]), GazeEventDuration (fixation duration), and participant (individual differences, with P01 as the reference). Given that pupil dilation was a continuous, positive-value response variable, we compared three different GLM families to identify the best-fitting model:

1. Gaussian GLM (normal distribution): assumes that pupil dilation is normally distributed with constant variance.
2. Gamma GLM (Log-link Gamma distribution): accounts for the skewness of physiological measures like pupil dilation, which is strictly positive.
3. Inverse Gaussian GLM: models highly skewed data where variance increases quadratically with the mean.

To assess whether the impact of gaze duration varies across AU types, we included an interaction term (AU_type × GazeEventDuration). Model selection was based on the Akaike Information Criterion (AIC), which balances model fit and complexity. The results indicate that the Gaussian GLM achieved the lowest AIC (-11048), followed by the Gamma GLM (-11033) and Inverse Gaussian GLM (-10876). Given the comparable AIC values, we prioritize the use of the Gaussian model for interpretation due to its intuitive linear relationship between predictors and pupil dilation.

The results, as presented in Table 4, suggest that translation processing type significantly impacts the cognitive load in English-to-Chinese translation. Specifically, ST processing leads to significantly lower pupil dilation than parallel processing ($p < 0.001$), while TT processing also reduces pupil dilation, though to a lesser extent ($p = 0.033$). These findings align with research indicating that text comprehension (ST) requires less cognitive effort than multitasking (parallel), whereas text production (TT) involves similar or slightly lower cognitive demands. Furthermore, gaze event duration influences cognitive load differently across processing conditions. Overall, longer fixations are associated with a slight decrease in pupil dilation ($p = 0.026$), potentially indicating adaptation or cognitive efficiency. However, in TT processing, longer fixations significantly increase pupil dilation ($p = 0.0026$), suggesting that sustained fixations during text production impose higher cognitive demands. This finding is consistent with prior research showing that fixations during writing require prolonged cognitive processing, leading to increased cognitive loads. In contrast, gaze duration does not significantly affect pupil dilation in ST processing ($p = 0.265$), suggesting that cognitive effort remains stable regardless of fixation duration during text comprehension. Additionally, participant differences were highly significant across all models ($p < 0.001$), reflecting individual variability in cognitive processing strategies. Some participants, such as P10, exhibited higher pupil dilation, suggesting increased cognitive effort, whereas others, such as P18 and P12, showed reduced pupil dilation, indicating differences in cognitive load management. However, given the complexity of these variations and their secondary relevance to the study's primary objectives, we omit a detailed discussion of participant differences.

Table 4. Interpretation of Gaussian model for English-to-Chinese translatiom, with a corresponding estimate and *p*-value with Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05.

Predictor	Estimate	*p*-Value	Interpretation
Intercept	3.138	<0.001 ***	Baseline pupil dilation (parallel processing, reference participant).
AU_typeST	−0.0356	<0.001 ***	ST processing significantly reduces pupil dilation compared to parallel processing.
AU_typeTT	−0.0140	0.033 *	TT processing slightly reduces pupil dilation relative to parallel processing.
GazeEventDuration	−0.000028	0.026 *	Longer gaze durations are associated with a small but significant decrease in pupil dilation.
AU_typeST:GazeEventDuration	−0.000018	0.265	Not significant: gaze duration does not significantly alter pupil dilation in ST processing.
AU_typeTT:GazeEventDuration	0.000039	0.0026 **	Significant: longer gaze durations increase pupil dilation in TT processing.

To analyze the average pupil dilation (AVGpupildilation) in Chinese-to-English (C-E) translation, we employed a Generalized Linear Model (GLM) as displayed above, but without an interaction term between AU_type and GazeEventDuration. Importantly, interaction terms between AU_type and GazeEventDuration were tested in previous models but were found to be non-significant. This indicates that the effect of gaze duration on pupil dilation does not vary meaningfully across translation processing types in C-E translation. As a result, we report the final model without interaction terms for a more parsimonious interpretation.

The results, presented in Table 5, indicate that translation processing type impacts cognitive load differently in Chinese-to-English translation. Unlike in E-C translation, where ST significantly reduced pupil dilation, in C-E translation, ST processing does not significantly differ from parallel processing ($p = 0.285$). However, TT processing leads to a significant decrease in pupil dilation ($p < 0.001$), suggesting lower cognitive effort during text production compared to multitasking (parallel processing). A key distinction from the E-C results is that gaze event duration significantly influences pupil dilation in C-E translation ($p < 0.001$). Longer fixation durations are associated with increased pupil dilation, suggesting that sustained fixations demand higher cognitive effort in this translation direction. However, no significant interaction effects between gaze event duration and AU_type were observed, indicating that the impact of fixation duration on pupil dilation remained stable across all translation processing types. Additionally, participant differences were highly significant across all models ($p < 0.001$), demonstrating individual variability in cognitive processing strategies. Some participants, such as P09, exhibited higher pupil dilation, whereas others, such as P18 and P13, showed reduced pupil dilation, indicating variability in cognitive load management. However, due to the complexity and secondary relevance of these variations, we omit a detailed discussion of participant differences.

Table 5. Interpretation of the Gaussian model for Chinese-to-English translation, with a corresponding estimate and *p*-value with Signif. codes: '***' 0.001.

Predictor	Estimate	*p*-Value	Interpretation
Intercept	3.092	<0.001 ***	Baseline pupil dilation (parallel processing, reference participant).
AU_typeST	−0.0077	<0.285 ***	Not significant: ST processing does not significantly differ from parallel processing.
AU_typeTT	−0.0475	<0.001 ***	TT processing significantly reduces pupil dilation compared to parallel processing.
GazeEventDuration	0.0000076	<0.001 ***	Longer gaze durations are significantly associated with increased pupil dilation.

The findings from our Generalized Linear Models (GLMs) highlight key differences in cognitive load between English-to-Chinese (E-C) and Chinese-to-English (C-E) translation. In E-C translation, ST processing significantly reduces pupil dilation, indicating that comprehension requires less cognitive effort than multitasking (parallel processing). Additionally, longer gaze durations generally decrease pupil dilation, except in TT processing, where sustained fixations increase cognitive load. In contrast, C-E translation exhibits a different pattern, where ST does not significantly differ from parallel processing, and TT processing still reduces cognitive effort. Notably, longer gaze event durations significantly increase pupil dilation across all processing types, suggesting that sustained fixations in C-E translation may indicate greater cognitive effort.

4.3. Retrospective Self-Reflections

In this study, participants' introspective accounts were gathered using cue-based Retrospective Think-Aloud (RTA) protocols. They were asked to articulate how they distributed cognitive resources between source text (ST) and target text (TT) processing in both translation directions—that is, to compare the effort invested in ST versus TT during English-to-Chinese (E-C) and Chinese-to-English (C-E) tasks. Comparisons between these subjective reflections and the objective data were conducted at a macro level. Participants' self-reflections are summarized below in Tables 6 and 7:

Table 6. Self-reflection: E-C translation.

	Allocation of Cognitive Resources to ST and TT				**Allocation of Cognitive Resources to ST and TT**		
	S1–3	**S4–6**	**S7–9**		**S1–3**	**S4–6**	**S7–9**
P01	60/40	50/50	50/50	P12	60/40	70/30	80/20
P02	40/60	40/60	40/60	P13	60/40	60/40	65/35
P03	50/50	60/40	60/40	P14	50/50	60/40	60/40
P04	50/50	50/50	30/70	P15	50/50	50/50	50/50
P05	30/70	40/60	50/50	P16	50/50	50/50	50/50

Table 6. *Cont.*

	Allocation of Cognitive Resources to ST and TT				Allocation of Cognitive Resources to ST and TT		
	S1–3	**S4–6**	**S7–9**		**S1–3**	**S4–6**	**S7–9**
P06	60/40	60/40	60/40	P17	70/30	70/30	70/30
P07	50/50	60/40	60/40	P18	40/60	40/60	50/50
P08	50/50	60/40	60/40	P19	70/30	70/30	80/20
P09	50/50	60/40	60/40	P20	50/50	40/60	50/50
P10	60/40	70/30	70/30	P21	60/40	70/30	80/20
P11	50/50	50/50	50/50	P22	50/50	50/50	50/50

Table 7. Self-reflection: C-E translation.

	Allocation of Cognitive Resources to ST and TT				Allocation of Cognitive Resources to ST and TT		
	S1–3	**S4–6**	**S7–9**		**S1–3**	**S4–6**	**S7–9**
P01	40/60	30/70	30/70	P12	30/70	30/70	30/70
P02	40/60	40/60	40/60	P13	50/50	40/60	40/60
P03	40/60	30/70	30/70	P14	30/70	30/70	30/70
P04	20/80	30/70	50/50	P15	30/70	20/80	20/80
P05	20/80	S	S	P16	40/60	40/60	35/65
P06	40/60	50/50	50/50	P17	50/50	40/60	40/60
P07	40/60	50/50	50/50	P18	30/70	30/70	20/80
P08	20/80	20/80	10/90	P19	50/50	45/55	40/60
P09	40/60	30/70	20/80	P20	50/50	50/50	40/60
P10	40/60	30/70	30/70	P21	50/50	40/60	30/70
P11	20/80	20/80	20/80	P22	50/50	45/55	30/70

In the case of C-E translation, participants' retrospective reflections obtained, through RTA, closely aligned with the eye-tracking and keystroke logging results. Most participants recognized that producing content in their second language required more time overall, a greater number of attention units (AUs), and longer durations per AU.

However, when reflecting on their E-C translation processes, many participants believed that they devoted more cognitive effort to understanding the English source text than to producing the Chinese target text. Of the 22 participants, only 4 (P02, P04, P05, and P18) reported allocating greater cognitive resources to TT production than to ST comprehension at any point. A small number (P11, P15, P16, and P22) perceived their efforts to be evenly divided between the two processing types. The majority, however, appeared unaware of the dominant cognitive load associated with TT production. Even among those who acknowledged investing more effort in TT production, their estimates were significantly lower than what the empirical data suggested—typically ranging between 30% and 40% of total cognitive effort.

For the majority of participants, the main difficulty encountered during L2-to-L1 translation stemmed from comprehending the English source text. Their strong confidence in producing text in their native language—rooted in familiarity and habitual use—appears to be a key factor contributing to the notable gap between their subjective assessments and the objective findings obtained through eye-tracking and keystroke logging. As participant P19 observed, translating from Chinese into English requires careful consideration of linguistic and cultural appropriateness. In contrast, during English-to-Chinese tasks, she experienced no hesitation during production and rarely reviewed her Chinese target text, trusting that it would naturally sound appropriate. Similarly, P22 noted that reviewing her output was unnecessary when translating into Chinese, describing the language as "too familiar" to pose any challenge.

Interestingly, even though most participants were unfamiliar with the formal concept of parallel processing in translation, several reflected on the overlapping nature of source text comprehension and target text production. Some also referred to the automatic nature of certain translation behaviors, particularly when working in their first language. These observations align with the findings of Hvelplund [12], who identified instances of automatic and parallel processing in English–Danish translation tasks, suggesting that either the input is passively retained in sensory memory during typing, or that keystrokes themselves occur without conscious monitoring.

Similar patterns emerged in the present study. Several participants reported that typing in their native language, especially for simple and frequently used expressions such as "所以" (so) or "但是" (but), occurred with minimal cognitive effort. As P12 described, the act of typing felt entirely automatic: "I just feel my fingers moving and typing without thinking". Notably, no such comments were made regarding English target text production during L1-to-L2 translation. Furthermore, in the context of C-E translation, participant P16 acknowledged the difficulty in separating ST comprehension from TT production, noting that the processes often overlapped—particularly when the Chinese source material was clear and easily understood.

To summarize, the eye-tracking and keystroke logging data reveal that participants exhibit diverse patterns of resource allocation across both translation directions, highlighting significant variations in translation strategies and cognitive approaches among individuals. Translation into English generally requires greater focus on the target text, likely due to the linguistic and stylistic challenges of producing fluent English, especially since the interpreters are not native English speakers. In contrast, translating into Chinese demonstrates a more balanced allocation of cognitive resources between the source text and target text, potentially reflecting lower cognitive demands for TT production in this direction. Both directions show an increased focus on the TT as tasks progress, but this trend is more pronounced in C-E translation.

This study identified instances of parallel coordination between source text (ST) comprehension and target text (TT) production among translators. Evidence from both the quantitative data and participants' self-reports supports the existence of a strong association between cognitive effort allocation and the type of processing involved. Eye-tracking and keystroke logging results indicated that TT processing consistently accounted for the largest share of cognitive resources. While many participants demonstrated awareness of the differing cognitive demands across processing types, their estimates regarding the distribution of attention units (AUs) often diverged from the empirical findings. When compared to the study's hypotheses, the results show that two of the three proposed hypotheses were fully supported, while the third received partial confirmation. The third hypothesis proposed that "there are differences between descriptive data and participants' self-reflection. For instance, participants may have a tendency to be unaware of the cognitive resources invested in first-language production during L2-to-L1 translation". This was partially validated by the findings. Additionally, some participants reported experiencing multitasking, parallel processing, and instances of automatic processing during translation tasks.

This study relies on eye-tracking and keylogging data to investigate cognitive resource allocation during translation. While these methods provide valuable insights, they inherently only capture a subset of the complex cognitive and physiological responses involved in the translation process. As a result, certain dimensions of translator cognition, such as emotional regulation and stress, may remain underexplored. Future research could address this limitation by adopting a multimodal methodology, incorporating additional tools such as facial expression analysis, respiratory monitoring, heart rate (HR) tracking, galvanic skin response (GSR), and cue-based Retrospective Think-Aloud (RTA) protocols. Such an integrated approach would allow for a more holistic understanding of the interplay between cognitive and emotional processes during translation tasks. Another limitation lies in the study's exclusive focus on novice translators. While this provides valuable insights into the translation behaviors of this specific cohort, the findings cannot be directly generalized to more experienced or professional translators, whose cognitive strategies and resource allocation may differ significantly. Investigating variations across translator groups with differing levels of expertise and professional backgrounds represents an important avenue for future research. Lastly, this study is constrained by its focus on the English–Chinese language pair. To enhance the broader applicability of the findings, future research could expand to other language pairs or replicate the study with a focus on Chinese-to-English translation. Such comparative studies would provide deeper insights into how language directionality and typological differences influence translation processes.

5. Conclusions

This study examined how novice translators coordinate source text (ST) and target text (TT) processing, revealing strong correlations between cognitive effort allocation and processing types. Our findings indicate that TT processing consumes the largest share of cognitive resources, as discussed regarding the GLMs. While most translators were aware of processing differences, their assumptions about effort distribution often diverged from the observed data. The purpose of this study was not to suggest that translators were 'wrong' in their perceptions but to explore how objective indicators of cognitive effort aligned with subjective experiences. Objective measures, such as eye-tracking, provide quantifiable data, while self-reports capture unique insights into translators' conscious attention and perceived difficulty. By integrating these methods, we aim to present a holistic understanding of cognitive effort during the translation process.

Our findings highlight that translators' subjective perceptions may not fully reflect underlying cognitive processes, emphasizing the importance of using multimodal approaches to study cognitive effort. The combination of objective measures and self-reports bridges the gap between externally observable cognitive effort and translators' subjective experiences, offering a richer perspective on attention allocation and perceived challenges at various stages of translation. These insights have broader implications for translator training and research. Developing metacognitive awareness of cognitive effort allocation could help translators manage their workload better. This study further contributes to debates on the reliability and validity of self-reports when assessing cognitive effort.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app15084401/s1, Supplementary File S1: Experiment Source Texts; Supplementary File S1: Experiment data.

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