"Psi equals craziness": Upper-division physics students' conceptions of Greek letters

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Symbolic representation is a cornerstone of mathematics and science. While much research has explored student understanding of various mathematical symbols, there is very little known about the way students conceptualize the use of Greek letters in scientific notation. In this work, we share excerpts from interviews with upper-division physics students, which illuminate their experience with Greek symbol use. The students reported frequently mistaking pairs of similar-looking Greek and Latin letters. They also felt that their texts and instructors had not sufficiently introduced novel Greek letters or explained what they represented in the equations. The students also disliked how often a single Greek letter would be used in multiple contexts – or that different texts and instructors would not follow the same convention for which letter to use in a single context. These observations suggest that educators should devote additional time to introducing and discussing Greek letters in scientific contexts.

I. INTRODUCTION

Symbolic representations are a critical component of mathematics and science [1, 2], and the prevalence and necessity of symbolic notation poses unique educational challenges for math-based domains [3]. Learning the norms and accepted practices of symbol use can take a significant amount of cognitive effort [4, 5], but this additional work is rewarded by the "considerable computational advantages" ([6], p. 11) which symbols provide. Symbols enable problem-solvers to bridge the gap between conceptual ideas and cognitive processes [7]. Thus, it is imperative that learners develop a rigorous understanding of symbol use in scientific contexts.

Unfortunately, many conventions around symbol use in math and science can be problematic. To start, symbol choice and syntax are often inconsistent between disciplines – as is often seen with mathematics and physics [4]. While most scientific communities will have an established standard, instructional materials may not adhere to them, symbol conventions may change between secondary- and university-level learning environments, and instructors may not sufficiently explain or address these inconsistencies [4, 8]. As a result of these ever-changing systems, a single symbol may appear across a multitude of contexts to represent wildly incomparable concepts [2, 4]; for instance, lowercase lambda 'λ' is used to represent wavelength, linear charge density, and the radioactive decay constant in physics, but also the average failure rate in engineering, eigenvalues in linear algebra, and longitude in geography!

The mutability of scientific symbol use places a significant burden on learners, all while they simultaneously develop content knowledge and problem-solving skills [5]. Multiple studies have found that students are much more able to solve numerical/calculation or verbal/word problems than the equivalent problems presented in a purely symbolic manner [9, 10], and that they struggle to provide verbal descriptions of symbolic expressions [11]. Categorizing, deconstructing, and evaluating the obstacles posed by symbol use in math and science remains a fruitful area of educational research. A great deal of research has focused on individual symbols, like the equals sign [12, 13] or trigonometric functions [14]. Others have investigated symbol syntax – such as subscripts [15] or the common/correct ordering and arrangement of equations [16, 17]. In general, these studies conclude that students would benefit from more direct and explicit discussion of symbol meanings and conventions.

One area that has received almost no attention is students' conceptions around the use of Greek letters. Modern mathematicians and scientists adopted the Greek alphabet to expand their symbolic lexicon [2]. Yet, despite their prevalence in scientific notation, researchers have not explored the ways in which Greek letters may present distinct challenges to students whose primary language uses the Latin alphabet. One of the few explicit mentions of Greek letters in educational research on symbol use comes from the work of Begg and Pierce [4], who advise in their discussion (p.23):

> "Greek letters are ubiquitous in this field, but many students have little or unrelated prior experience with them. Introducing students to the entire Greek alphabet including case, phonetics, and how to write them can help to make these symbols less of an obstacle for students."

Although this was offered as an implication for teaching, the data presented in their work focused on the difficulties which arise from using a large number of symbols and/or inconsistent notation; no data was presented to showcase examples of students interacting with or reacting to the use of Greek letters specifically, nor were there comparisons of students' conceptions around Greek and Latin letters.

In this paper, we present excerpts from interviews with upper-division physics students to better understand their lived experiences with Greek letters as scientific symbols.

II. THEORETICAL FRAMEWORK

In the wider expanse of academic literature, there are many theoretical frameworks which examine or deconstruct the nature of symbolic reasoning in a broad or generalizable sense; in these, the term 'symbol' refers to any communicative tool which represents a conceptual object other than itself. For our work, we must narrow that scope considerably; we use 'symbol' to refer to the unitary glyphs used in mathematical contexts to stand in for numerical values or mathematical operations – or sometimes, both [7]. For our analysis, we use the framework presented by Serfati [18], which assesses symbols in mathematical notation along three axes:

- *Materiality*: the visual appearance of the symbol and the ontological category from which the glyph is drawn (e.g., letter, number, or shape).
- *Syntax*: the accepted conventional practices/rules regarding placement or spatial organization of the symbol in relation to other symbols in an expression.
- *Meaning*: the conceptual object being represented by the symbol and its relationship to surrounding context.

By examining students' conceptions of Greek letters along these three dimensions, we can better identify challenges which may be present within (or perhaps even unique to) this under-studied category of mathematical symbol.

III. METHODS

The data for this paper come from the *PhysMath* project [19], which sought to understand how upper-division physics students coordinate mathematical and conceptual ideas. Throughout the spring 2024 semester, students enrolled in the Classical Mechanics course at our university were invited to participate in one-on-one, semi-structured interviews. Each interview was roughly 90 minutes in length and consisted of two parts: a discussion and an activity. In the discussion, the interviewer asked participants to explain their current understanding of a recent topic from the course (both the concept and its related mathematics) and describe their learning/problem-solving experiences around the topic. The activities varied from week to week depending on the topic, but included tasks like deciphering physics equations with anonymized symbols, imagining hypothetical worlds in which common physics equations were altered, and trying out digital simulations developed by the research team which included interactive equations; each activity was designed to make visible the students' coordination of conceptual and mathematical ideas related to the chosen topic. Four students volunteered to participate, resulting in 23 interviews ranging across 7 topics.

The first week's topic was the use of symbols in physics equations. The students were asked to explain the patterns and norms they had observed in symbol use, both in physics and other domains in which they had experience – such as mathematics, engineering, and/or computer science. They were also asked to describe any challenges they had encountered with symbols in their coursework. The activity for the week was a card-sorting task, where the students were given a deck of 60 cards with various Latin and Greek letters and asked to rank them along a five-point scale (Definitely, Likely, Neutral, Unlikely, Definitely Not) according to several prompts, such as "*even without seeing it in an equation, I know what this symbol means*" and "*this symbol represents a physical quantity in the real world.*"

Video and audio recordings were taken at each interview. The transcriptions were first analyzed using a grounded approach [20], where noteworthy moments were given descriptive codes before iterative analytical passes looked for patterns between codes. When several of our emerging codes from the first week pertained to the students' understanding of Greek letters, we searched through related literature to find a more targeted theoretical framework for symbol analysis – leading us to the work of Serfati mentioned previously [18].

IV. FINDINGS

In this work, we share excerpts from the interviews of all four participants, who have been given the pseudonyms Vera, Florence, Cooper, and Reuben. The experiences these students shared regarding Greek letters led to four emergent coding categories: *discriminability issues*, *unclear descriptions*, *abstract associations*, and *inconsistent use*.

A. Discriminability Issues

All four participants had trouble recalling the names of various Greek letters. Vera couldn't recall the name of one of the Greek letters she had seen used in boundary-value problems, saying, "here, they use xi and, I already forgot what the other one was called." She also mentioned that her Classical Mechanics instructor had recently used an unfamiliar Greek letter (uppercase Gamma 'Γ') and could only describe it as "it looks like an 'r.'" During his card-sorting activity, Cooper had to ask for the names of the nu 'ν', lambda 'λ', and epsilon 'ϵ' cards, even asking on the last one, "is that Greek, or is that something else?"; later, Cooper would accidentally call the nu 'ν' card "eta" without noticing. Reuben's first guess when encountering the Psi 'Ψ' card was to guess "capital Phi?" Florence felt hesitation even when she got her identifications correct; upon seeing the omega 'ω' card, she responded, "that one's omega, right? Now I'm so scared I've got all my Greek letters wrong."

The students also had difficulty differentiating some Greek letters from Latin letters with similar appearances, especially when hand-written. The instructor's use of Gamma 'Γ' gave Vera difficulty because it was in an equation for torque, which also includes 'r' for radius; she lamented, "my handwriting isn't good enough to make the two different." Vera went on to identify several other troublesome pairs of Greek and Latin letters: alpha 'α' and 'a', beta 'β' and 'B', and tau 'τ' and 't' "if I don't make it swirly. I purposely make my Greek letters very squiggly to try to make it more obvious." Cooper's strategy was to avoid handwriting completely; he explained that his hand-written alpha 'α' often wound up looking too similar to the proportional symbol '$\propto$'. He, too, had trouble deciphering some of the symbols written by the instructor on the whiteboard, specifically in differentiating rho 'ρ' from 'p' (a duo which was also called out by Reuben and Florence) and mu 'μ' from 'u.' Reuben flagged omega 'ω' and 'w' as another potential mix-up, along with lowercase phi 'ϕ' and uppercase Phi 'Φ'. Sometimes, a lone Greek symbol was trouble enough. Cooper expressed frustration at xi 'ξ' for being "a garbage symbol. You just [waves hand chaotically through air], we basically do that to write it. I guess it's fine if you're going to type it, but just writing it, it's kind of precise to make it not just a squiggle."

We even observed *discriminability issues* occur in real-time during the interviews when both Vera and Florence assumed the hand-written letter on the nu 'ν' card was the Latin 'v.' When Florence later found the true 'v' card, she realized the possible duplicate and backtracked to the nu 'ν' card, asking "is this one rho?" Vera, on the other hand, did not notice the duplicate for the duration of the activity and sorted both cards without reconciliation.

B. Unclear Descriptions

One locus of frustration for the students was the tendency of instructors and texts to not sufficiently introduce and/or explain novel Greek letters when they arose in the course material. Vera was used to having to look up Greek letters that appeared in the textbook – implying that the text itself had not identified the letter for her. She commented, "I feel like every single course, I'm learning a new Greek letter that I hadn't known before... it makes it hard, because they need to state out what that Greek letter is supposed to represent before I'm like, 'oh, that's what it means."' The lack of clarity was apparently not unique to Vera's physics courses; she shared:

> "With the Partial Derivatives class, they just went into writing equations and using a bunch of Greek letters, and I'm like, 'what is that supposed to represent?'... at least I know I'm not the only one, because also other people in class are like, 'what does that letter mean again?"'

Vera clarified that these experiences had been with Greek letters which she could name and identify – it was their symbolic meaning which had not been adequately explained.

Cooper expressed a similar frustration around encountering new Greek letters without proper introduction, saying:

> "When you see the [Latin] letters, it's like, 'oh, I know what that letter is.' But if you see a Greek letter the first time, I don't even know what that means. I don't know how to say that. I don't even know how to look that up. I may not even know if it's Greek."

He said that he wished instructors would spend a few moments explicitly discussing the names, origins, and conventions of unfamiliar symbols for students who may have never seen them before.

C. Abstract Associations

In some cases, the presence of a Greek letter brought with it assumptions and preconceptions about the nature of the represented concept. Cooper's past experience with challenging equations containing unusual or rare Greek letters left him feeling hesitant around the whole bunch:

> "With Greek letters, it can be kind of like Psi, where it speaks to me as something that's a little bit more nebulous... there is something that is capital Psi or capital Phi, I don't remember what it is, where that's like, 'oh yeah, this is a whole thing!' Maybe it's just because Greek letters are scary. You're just burned by quantum mechanics, where it's like, 'Psi equals craziness."'

He later added that, "Greek letters are foreign, so it's like 'oh, if they're using that symbol there instead of something like capital 'A,' there must be something scary."'

D. Inconsistent Use

Unsurprisingly, the students shared numerous cases in which they had seen symbols used interchangeably or inconsistently, and many of their cited examples included changing conventions around Greek letters. Vera's previous university had used lambda 'λ' and beta 'β' in boundary-value problems (compared to using xi 'ξ' and the unknown letter at her current university). Cooper complained several times about the swapping of theta 'θ' and phi 'ϕ' between mathematics and physics courses when referring to the 180- and 360-degree angles present in spherical coordinate systems. He proclaimed:

> "I think math wins on this one, because they teach you the math way since seventh or eighth grade when they introduce the unit circle, 'this is an angle, it's theta'... and then, physics, now in Classical Mechanics, they're like, 'no, the 360 degree angle, that's phi, and the 180 degrees, that's theta.' It's like, no! I refuse!"

The angle variables were not the only source of frustration across courses for Cooper; he commented that, "in Physics 1, tau was torque, but here in Classical Mechanics, capital Gamma is torque. In Differential Equations, tau can be a different thing too that I can't remember." Similarly, Reuben pointed out how often tau 'τ' had been used across numerous contexts:

> "It's used to represent torque... in Intermediate Modern Physics, we used it to represent proper time... it was used in the textbook in Classical Mechanics as part of an equation related to the quadratic term of air resistance – I think they use it as a placeholder... Having arbitrary representations like that is confusing when they're typically used in another way as well."

When Vera was asked what she would change about notation in physics if given the chance, her answer specifically called out inconsistent use of Greek letters; she exclaimed, "Just be consistent! Like a universal, everybody agrees 'this is what this Greek letter means.' That's what I wish." Her feelings around the Greek letters' unreliability emerged again during the card-sorting activity as she sorted symbols under the "*even without seeing it in an equation, I know what this symbol means*" prompt. When explaining her choices for the 'Definitely Not' category, she remarked:

> "I feel like I've constantly seen gamma, alpha, beta, delta, I've seen those used everywhere. It feels like a lot of the Greek letters, those haven't been very consistent throughout my courses... I've seen them everywhere for different things. I feel like I wouldn't know exactly what they mean if I was given one."

In spite of these challenges, Vera stated that she had eventually come to appreciate the Greek letters, but wished her exposure to them had been more gradual:

> "Now, I really like Greek letters because it's what I've been using all throughout my college career. I just wish that I'd been introduced to it sooner, like in high school... it was a sudden jump to Greek letters... that was tough."

V. DISCUSSION

Our interviews with upper-division physics students revealed several challenges related to the use of Greek letters as scientific symbols. The *discriminability issues* we observed – forgetting Greek letters' names and mistaking them for similar Latin letters – show how our students have struggled with the *materiality* [18] of Greek letters to some extent. The other three coding categories – *unclear descriptions*, *abstract associations*, and *inconsistent use* – were all connected to the *meaning* of Greek letters, revealing this axis to be the most represented in our findings. We did not observe any examples of difficulties with the *syntax* of Greek letters. On this axis, we do not expect Greek letters to have unique challenges compared to Latin letters as either category of symbol can be placed within equations or other mathematical structures in more-or-less identical manners. On the whole, our findings agree with the broader trends seen in previous reports on symbol difficulties across math and science [2, 4].

We must note that the challenges we observed were not entirely sequestered to Greek letters. For instance, there were examples in our interviews when students had *discriminability issues* with hand-written Latin letters, like distinguishing lowercase 'l' from uppercase 'I' or determining if a 'c/C,' 's/S,' 'v/V,' or 'x/X' was capitalized. Similarly, our students mentioned several examples of *inconsistent use* that included Latin letters, like when Florence recalled having to ask herself "is this x representing distance, or is this x just an arbitrary variable?" or Cooper commenting that both lowercase 'n' and uppercase 'N' are often used interchangeably to represent the number of objects or items in a group or summation. However, our students shared considerably more examples involving Greek letters than they did with Latin letters. In fact, the students commonly called out Greek letters directly even when the interviewer's question had not specified one alphabet or another. Vera and Cooper were the most direct in their singling out of the Greek alphabet; Vera explicitly stated that the Greek letters "haven't been very consistent," and Cooper described Greek letters as being "more nebulous." These students' accounts and the relative abundance of Greek examples in our sample do not immediately prove that Greek letters or more prone to symbolic challenges than Latin letters, but they indicate that there may be an imbalance between the alphabets. At the very least, we feel there is a need for further investigations to determine if Greek and Latin letters are used more or less consistently than each other in a generalizable or systematic manner in physics instructional materials.

Even still, we believe our findings point to several extenuating factors, which may amplify the difficulty of understanding Greek letters in physics contexts beyond that of their Latin counterparts. Our students cited the foreign nature of the Greek alphabet and its sudden and rapid introduction years after they had become fully accustomed to using the Latin alphabet alone as unique hurdles they had experienced when learning Greek symbols. This lack of familiarity was made apparent by the many instances we observed of the students forgetting the names of Greek letters and calling Greek letters by the wrong name – an issue that does not exist for the Latin letters. The most egregious disparity between the alphabets was seen between the numerous pairs of Greek and Latin letters that, to borrow a term from graphic notation, fail to have sufficient "perceptual discriminability" (Ref.[21], p. 763). In every case in which we saw our students come across one of these ambiguous pairings, their first instinct was always to assume that the letter was Latin. While our sample size is quite small, we believe it is reasonable to expect this pattern in general populations, as such a heuristic would prove to be trustworthy in the vast majority of circumstances. Together, the confluence of students' lack of familiarity/experience with Greek letters and the similarity of many of the Greek letters to Latin letters will likely exacerbate any other challenges that may be present with (but not unique to) Greek letters.

VI. CONCLUSION

Our findings suggest that there is more to be understood regarding learners' conceptions around Greek letters as a category of scientific symbol. Going forward, it could be informative to investigate how the degree of inconsistency with Greek letters across instructional materials compares with that of Latin letters (or other symbol/notation categories). Similarly, qualitative explorations of learners' experiences with Greek letters – perhaps across different ages and grade levels, or with participants whose primary languages do not use the Latin alphabet – may uncover further details about the ways Greek letters perform as scientific symbols.

For educators, we recognize that explicitly discussing the *meaning* of symbols is likely already an instructional priority. When these discussions are directed at Greek letters, we encourage instructors to expand the discussion to also include *materiality* by providing the name (preferably, written out) and origin of the symbol to aid students who may be encountering it for the first time. Furthermore, we would suggest that these discussions not merely be the instructor conveying information on the symbol to the students. Each student brings with them their own unique history of courses, texts, instructors, and institutions. We believe that any successful discussions around *inconsistent use* must necessarily include inviting students to share their experiences so that guidance can be customized to fit the needs of the classroom. In these ways, educators can provide additional support to students as they navigate the many possible contexts and uses of Greek letters and other novel scientific symbols.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation (2235569).

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