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The Yale Science & Engineering Association congratulates YURJ on the publication of its inaugural Research Journal!

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YURJ would like to further extend its thanks to the Department of EEB and Saybrook College for their support.
Foreword By Professor James Rothman

I am grateful to the Editors of the Yale Undergraduate Research Journal for their invitation to write a Letter about the importance of undergraduate research at Yale for this inaugural print issue.

Doing so has special meaning because it causes me to reflect on the importance of the research I did as a Yale College student to my development as a scientist. One of the great attractions of Yale then and now is the breadth of scholarship (and personalities) that our community embraces among the natural sciences (which we now call STEM), the social sciences, and the humanities. This allows each of us to explore the full range of opportunities at the limits of knowledge which define the border which we seek to traverse by what we call research. The content of this issue very well reflects this.

There is also great breadth and collaboration within the several disciplines that comprise STEM, and Yale provides, especially through the residential college system, a potent means to form personal and fledgling professional relationships. In my case, I was a physics major but transited during my junior year via my first research project in physical chemistry to biophysics research in my senior year. While the research itself was of no special or enduring importance, the pathway of personal development and the senior scientists who influenced me were of absolute importance for shaping the scientist I would soon become, and for my path ever since. Most notable was Don Engelman, then junior faculty and still an active member of MB&B. My autobiography (https://www.nobelprize.org/prizes/medicine/2013/rothman/biographical/) outlines this multi-year process by which I gradually learned to think like a biologist, while still retaining the orthogonal way of thinking of a physicist. I believe this mindset was critical not only for my choice of the problem whose solution was recognized by the Nobel Prize, but also in providing me the means to solve it. The same dynamic still defines the way I approach science today.

It is my hope that each of the current undergraduates whose research is highlighted here, and as importantly the many more that could not be accommodated, will have been influenced by their research experience and mentors at Yale in equally as profound yet individual ways, whatever and wherever your futures take you. In my day undergraduate research was not especially emphasized and though certainly not discouraged. There were few if any programs or systematic processes to encourage or enable research. Today, from recruitment and outreach during the admissions process to abundant (but never abundant enough) summer fellowships, and many other mechanisms, a special premium is happily being placed on a research experience. I salute the organizers and editors of this Journal for contributing to this in such a singular way by highlighting some of your achievements.

Sincerely,

James E. Rothman ‘71
Resident Fellow of Branford College
Sterling Professor and Chair of the Department of Cell Biology
Director, Yale Nanobiology Institute
LETTER FROM THE EDITOR

Dear Reader,

We are thrilled to present you with the inaugural issue of the Yale Undergraduate Research Journal, the first publication spanning the full breadth of undergraduate research conducted at Yale. In creating this journal, we provide a platform to engage with the thoughtful, exciting, and cutting-edge work of our peers.

As we release this issue into the world, we would be remiss in failing to discuss the current state of affairs. Our world is one plagued by two crises, COVID-19 and systemic racism. Besides precipitating immeasurable tragedy, the virus’s spread has also slowed, stalled, or halted much of the research conducted at academic institutions. Alongside the increasing number of victims lost to coronavirus, the devastating deaths of Black Americans—including those of George Floyd, Breonna Taylor, and countless others—prompt us to put research in perspective, to consider its role in a disaster-stricken, divided, and unjust society.

Only through research, though, with meticulous quantitative and qualitative methods, can we deeply understand the root causes at play and begin to create enduring plans for change—whether developing a vaccine or dismantling oppressive structures. Now, more than ever, it is vital that we reaffirm the importance of pursuing truth, engaging in critical study, spreading awareness, and taking bold action to move society forward.

Over the past several months, our team has worked tirelessly to bring you the best research in the undergraduate community. We received more than a hundred submissions encompassing over 45 disciplines across the humanities, the social and natural sciences, engineering, and mathematics. Each submission underwent rigorous review by graduate students, postdoctoral fellows, and professors. We would like to thank our dedicated reviewers, faculty advisors, staff, and contributing peers for making this issue possible.

As you read through these pages, we hope you will find yourself as inspired and illuminated as we have been. In the coming months, we will continue to publish stellar research on our website at yurj.yale.edu and look forward to another round of submissions at the end of the fall semester.

In pursuit of light and truth,

Lukas Corey
Editor in Chief
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For a New Ethics of Reading: Analyzing *Tea in the Harem*'s Reception

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ABSTRACT

This paper examines the extratextual materials that reified the novel/film *Tea in the Harem* as an archive of knowledge about the *beur* community. I argue that *Tea in the Harem* was subjected to what I call an anthropological approach to literature, a reading practice which instrumentalizes and subordinates the text to the historical reality which it is said to represent. Though in many ways entangled with the principles of French republicanism, the reception of *Tea in the Harem* is symptomatic of a more general phenomenon in which literatures of “the other” are expected to rehabilitate, educate, and civilize the majority mind through their treatment of sociopolitically sensitive subjects. Charting the way for a new ethics of reading, this paper interrogates the prevailing value system which all too easily demands of socially marginalized authors an “authentic” representation of their reality, limiting authorial imagination to mere mimesis.

The March for Equality and Against Racism (La Marche pour l’égalité et contre le racisme) left Marseilles on October 15, 1983, responding to the increase in racist sentiments in France and protesting the police violence routinely faced by youth of North African heritage in the *banlieues.*¹ Two months later, what began as a small group of participants, mostly descendants of North African immigrants from Minguettes, turned into one of the most politically significant moments in French history, as more than 100,000 participants, including government ministers, labor leaders, and members of religious organizations, arrived in Paris for a final demonstration (“La marche pour l’égalité et contre le racisme”).

The March of the Beurs (La Marche des Beurs), as the movement came to be called, brought attention to issues of housing discrimination, police brutality, immigration, and citizenship, but it also left an indelible mark on the subsequent journalistic and scholarly treatment of “*beur* writing.” As previous scholars have pointed out, Mehdi Charef’s *Tea in the Harem* (Le Thé au harem d’Arché Ahmed), published in 1983, and its film adaptation in 1985 were sociopolitically overdetermined by the events of the March. As the *beur* political movement came to occupy an increasingly central position in the political consciousness of mainstream French society, *beur* writing became a stand-in or pretext for political discourse. *Beur* authors, who were often asked to comment on issues of “identity politics, immigration, and discrimination in French society” during their television and radio appearances, were reduced to the function of a native informant, tasked with the responsibility of making their minority culture intelligible to a majority audience (Kleppinger 25). Additionally, their works were subjected to what I call an anthropological approach to literature, a reading practice which, by studying, evaluating, and interpreting fiction in respect of its presumed portrayal of a historical reality, instrumentalizes and subordinates the text to the reality which it is said to represent. This essay examines the extratextual materials that reified the novel/film *Tea in the Harem* (and its author/director Mehdi Charef) as an archive of knowledge about the *beur* community. While acknowledging the extent to which the novel/film lends itself to an anthropological reading, the paper explores dimensions of Charef’s work that have been deemphasized in favor of narrowly racialized readings.

In elucidating what I have called the anthropological approach to literature, I draw on the works of Gayatri Chakravorty Spivak and Nayoung Aimee Kwon. In her seminal “Three Women’s Texts and a Critique of Impe-
rationalism,” Spivak famously dismisses “an information-retrieval approach to ‘Third World’ literature,” a reading practice which reduces the literary text to an archive of knowledge to be gained about the Third World (243). Such cases of information retrieval are legitimized by the same sociopolitical forces which have engendered what Kwon calls the “postcolonial regime of colonial rationalism,” a “dominant postcolonial rereading of the colonial past” which values colonial-period texts only insofar as they represent an “authentic” colonial reality (182). Both hermeneutics posit an unproblematic, referential relation between the literary work and its material context and in so doing renders the text predictable. In the same conceptual vein, the anthropological approach to literature, which is more interested in viewing the text as a cultural repository than in the text’s generative capacity to do what cannot be done in the material world, reduces the text to the function of a native informant, “the person who translates her culture for the researcher, the outsider” as both the source and the object of knowledge (Khan 2022). The term as I deploy it signifies both a reading strategy and a value system motivating our activities as readers. As an interpretive framework, it relies on an unreflective assumption that literature passively reflects a historical reality; as an evaluative framework, it influences which texts we choose to read and the standards by which we appraise them. As this essay will demonstrate, the novel/film Tea in the Harem was overwhelmingly subjected to an anthropological reading, made to explain a particular narrative of contemporary history, often to the neglect of its formal features.

In Branding the ‘Beur’ Author: Minority Writing and the Media in France, Kathryn Kleppinger investigates the process by which authors of the beur population became native informants for a mainstream French audience. In her monograph, she examines the role of audiovisual media as a significant extratextual force in the social construction of beur writing, which became coded as autobiographical and politically engaged. She astutely points out that the phenomenon resulted from a convergence of interests. “Journalists seeking to promote the contemporary relevance of the guests on their [television and radio] programmes” treated authors of North African heritage as spokespersons for the beur community, desiring their commentary on contemporary social issues (Kleppinger 119).

In turn, the authors, by “[accepting] this framing and [expanding] upon it,” actively participated in the social construction of their literary works as archives of knowledge about the beur community at large (119). “By establishing themselves as privileged interlocutors regarding such themes, these authors [solidified] the idea that such topics [constituted] the primary interest and goal of their work,” Kleppinger submits, later citing Mehdi Charef as a typical author in this category (25, 39). Her research casts light on the complex, dynamic process by which beur-authored texts ended up in the service of readers who wished to be introduced to relevant social issues in an easily digestible narrative format.

To this discussion of extratextual forces I add my analysis of print media, namely film reviews of Tea in the Harem, which unfailingly underscored the autobiographical overtones of Charef’s work. “[The film is] set in lower-class suburban Paris, partly in the Gennevilliers housing project where the young writer-director, Mehdi Charef, spent his teen-age years—living the same experiences that his teen-age protagonist Majdid (Kader Boukhanef) does in the

movie,” reads a July 18, 1986 Los Angeles Times review (Wilmington, “Movie Reviews: ‘Tea’: Outsiders in Mean Streets of Paris”). The passage, a particularly egregious example of the anthropological approach to literature, collapses all boundaries between the film’s protagonist and its director, grossly overgeneralizing their experiences as being one and the same. Moreover, that the review is American suggests that the reception of beur cultural production, though in many ways entangled with French republicanism,⁴ is part of a more general phenomenon in which literatures of “the other” are viewed as resulting from a particular cultural identity rather than from a singular, innovative, and idiosyncratic artistic mind. In so doing, the dominant culture withholds from “the other” the possibility of universal expression, which it silently reserves for itself. By gesturing to Charef’s personal background, the critic applies a specific reading practice

⁴A universalist belief that all citizens are equal before the law. The term, however, often conceals fundamental tensions in French society, which is becoming increasingly ethnically diverse.
to the film, decoding it as an “authentic” representation of life in the French housing projects.

This conflation of the cultural product with the cultural producer is unsurprising given that Charef himself frequently emphasized his personal experiences as the son of Algerian-born parents raised in a housing project in his television and radio appearances. Such slippages nevertheless give away a value system which all too easily demands of socially marginalized authors an “authentic” representation of their reality. For instance, a New York Times review, published on June 6, 1986, is particularly revealing for what it praises—and laments—about the film and is worth quoting at length:

Mr. Charef’s knowledge of what existence is like in a French housing project… comes through [in the film.] He is at his best in carrying us into those busy apartments, where every day brings a domestic skirmish or worse. These are people on the outskirts of French society, some of them on the outskirts of existence. It’s a combat zone between the have-little and the have-less, between those with jobs who are trying to hang on and keep their children from going bad and those with nothing left to lose.

A strong subject - but as though mistrustful of what he has to tell us about their struggles, Mr. Charef resorts to plot devices that seem to have been lifted from paperback novels. An unemployed young mother, one leg over the terrace railing, is stopped from suicide by the sight of her son, held up in the nick of time by the quick-thinking Madjid. Pat’s sweet sister is driven to street walking - and who should approach for purposes of proposition but her devoted admirer, young Madjid? Madjid’s mother, a pious Moslem, seems to have imported her lines from the Yiddish stage. (Goodman, “Screen: ‘Tea in Harem’”)

In this review, the critic assumes the film’s representation of life in the French housing projects to be faithful, envisioning a referential relation between Tea in the Harem and Charef’s lived experience. As the critic would have us believe, the film, thanks to Charef’s “knowledge of what existence is like in a French housing project,” reflects or refers back to a social reality in which “every day brings a domestic skirmish or worse.” Moreover, Goodman conceptualizes said representation as fundamentally passive and straightforward, as evinced in the following statement: “He is at his best in carrying us into those busy apartments.” According to the critic, Charef, in rendering the French housing projects into fiction, leaves them wholly untouched in the process. They are not reworked, contested, or reconfigured by the literature—rather, they are simply reproduced for the voyeuristic gaze of the film’s audience, who are provided with an insider’s perspective on a population “on the outskirts of French society.” However unwittingly, the critic forecloses the generative capacities of the film: authorial imagination is here limited to mere mimesis.

Moreover, the review unveils an anthropological evaluative framework in that the critic praises Charef for his knowledge of a fraught social reality and leaves unmentioned the role of artistic imagination in the rendering of that reality into fiction. “He is at his best in carrying us into those busy apartments,” Goodman appraises, but how Charef accomplishes this—his use of surface form to draw viewers into the experience of meaning—is seemingly of no concern. In fact, while the review commends the “strong subject” of the film, it finds fault with its “plot devices that seem to have been lifted from paperback novels,” citing among other examples the suicidal scene in which Josette nearly jumps from her balcony but is stopped by the sight of her son Stéphane. Unbeknownst to the critic, the scenes he disapproves most are those in which Charef’s authorial imagination happens to be most exercised: although the real-life inspiration for the Josette figure did commit suicide, Charef changed the outcome in his novel/film. “Je n’ai pas voulu faire un drame social et misérabiliste,”4 he explains in a later interview (qtd. in Hargreaves 139). The critic’s suspicion that the plot device results from the director’s “[mistrust] at what he has to tell us about their struggles”5 betrays the criterion by which we assess minority cultural production: as a vehicle for conveying a given social reality.

Likewise, the aforementioned L.A. Times review also promotes a value system which prizes works by marginalized authors primarily for their treatment of sociopolitically sensitive subjects and relegates the aesthetic experience of those works to a secondary concern. Titled “Movie Reviews: ‘Tea’: Outsiders in Mean Streets of Paris,” it too melds the artist with the art object in gesturing to Charef’s outsider status:

Charef is an outsider in more ways than one: Algerian, ex-factory worker, son of an unskilled laborer. One of the strengths of this unusually fine, perceptive, evocative first film is the way he ad-

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4 “I didn’t want to write a sordid melodrama” (Kleppinger 62).

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juxtaposes the audience, almost at once, to an outsider’s viewpoint. As in “Los Olvidados” or “Pixote,” we simply plunge in with the characters, live their world for a few hours and gradually understand what drives them to a life that seems initially amoral, empty and ruthless. (Wilmington)

The critic locates the film’s strength in its ability to “[ad]just the audience, almost at once, to an outsider’s viewpoint,” rendering transparent the formerly inscrutable lower class of France’s banlieues. In this way, the review makes legible the majority culture’s desire to gain access to the other, its “demand for intercultural information,” which constitutes part of the web of sociopolitical forces in which Tea in the Harem was and is suspended (Miller 2-3) Wishing to “understand what drives them [the minority] to a life that seems initially amoral, empty and ruthless,” the critic praises the film for humanizing the inhabitants of the French housing projects; yet this humanizing representation is only necessitated by—and derives its value from—the very dehumanization of the housing projects by the mainstream media in the first place. The minority artist is thus made to rehabilitate, educate, and civilize the majority mind and is rewarded for it.

In examining the extratextual materials that contributed to an anthropological reading of Tea in the Harem, I wish to avoid a rigid dichotomy in which either the text or the extratext is solely responsible for shaping the reception of the novel/film. If Tea in the Harem was easily co-opted by a journalistic and scholarly discourse which projected a political dimension onto the novel/film, such reading practices were assuredly sanctioned by textual as well as extratextual forces. In the film’s opening shot, for instance, the camera follows Josette and Stéphane as they walk, hand in hand, to Malika’s apartment, where Stéphane is to be dropped off. The audience’s initial entry into the world of the film is thus a quite literal one. In fairness to the New York Times review, Charef does indeed “[carry] us into those busy apartments” as the audience, adopting the point of view of the camera, is led inside the bustling interior of Malika’s residence (Goodman).

Nevertheless, Tea in the Harem exceeds the interpretive categories that have been placed upon it in at least one meaningful sense, accommodating critical lenses alternative to the racialized one which is so often deployed in analyses of the novel/film. As Kathryn Kleppinger aptly observes, the back cover of the 1988 edition of Le Thé au harem d’Archit Ahmed foregrounds Madjid’s identity crisis as the son of North African immigrants as a central theme of the novel: “Une cité H.L.M. Sur les murs: graffitis, slogans, appels de détresse, dessins obscènes. Madjid vit là. Il est fils d’immigrés, paumé entre deux cultures, deux langues, deux couleurs de peau, et s’invente ses propres racines, ses attaches,” it summarizes (qtd. in Kleppinger 36). Amazon, advertising Ed Emery’s English translation of Le Thé au harem, also spotlights Madjid’s racial background in its economic description of the novel, which reads, “the lives of second-generation Algerians in a Paris housing project, the basis of the award-winning film” (“Tea in the Harem”). Such racialized synopses evoke the beur political movement and bespeak the social relevance of the marketed text. But if the way editors, printers, and publishers presented Charef’s work was informed by a political consciousness increasingly preoccupied with France’s immigrant community, academics were hardly exempt. An article published in The French Review depicts “Le Thé au harem d’Archimède… [as] a novel about the misunderstanding and fear caused by institutionalized racism and poverty” and as “an incisive critique of the French attitude towards immigrants and the poverty that results” (Xavier 331). These paratextual and extratextual materials refied an interpretation of Tea in the Harem as an assertion of a particular cultural identity, namely, that of second-generation Maghrébines in France.

However, some scholars have begun contesting this interpretive framework, pointing to the ways in which Tea in the Harem exceeds or escapes a narrowly racialized reading. The film, for instance, makes use of a “doubling-up of central protagonists with different ethnic origins,” who nevertheless share the same working-class background, to emphasize themes of solidarity between alienated youths (Tarr 329). The multiethnic gang, whose members reside in the same housing project, moreover integrates individual ethnic identities into a unified whole, defined by their shared rebellion against the older generation (329; Xavier 333). It is in this way that the film resists a rigid adherence to a racialized framework and instead invites a com-
mentary along the lines of youth and age, friendship and alienation. In light of these alternative reading strategies, Malika, whose strained relationship with her son is typically regarded as emblematic of his dissociation from his mother country, takes on new significance. Madjidi’s acts of disobedience can be productively read alongside those of the other gang members toward their parents and other adults as a manifestation of intergenerational conflict, the tensions arising from which animate the film.

This rereading of the Malika figure brings to light what is elided by the anthropological approach to literature, which seeks to access the other through the semantic content of a literary text and, in so doing, consigns minority writing to the role of native informing. Although the disconnect between mother and son can undoubtedly be read as an allegory of the immigrant experience—“paumé entre deux cultures, deux langues, deux couleurs de peau”—its generative potentialities would be regrettably limited by a routine (and unreflective) usage of this critical lens (qtd. in Kleppinger 36). The native informant model, which provided Mehdi Charef and other beur authors with a platform for addressing relevant social issues, may have exhausted its political usefulness. In charting the way for a new ethics of reading, one must reexamine the demand all too easily placed on minority writing to faithfully—and affectingly—depict their tribulations to a majority audience so that it may be edified. Rather than fixating on the production of authentic knowledge of otherness, one would do well to attend more closely to the formal, non-mimetic, creative, and universalizing features of minority writing. Only by rejecting such reductionist models will we be able to disclose the aesthetic creativity and perpetual newness of these literary and filmic texts.

5 “Caught between two cultures, two languages, two skin colours” (Kleppinger 36).

REFERENCES


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Environmental Racism in Historical Context: The Robbins Incinerator Debate, 1980s-1990s

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ABSTRACT

Conventional narratives of environmental racism paint a “perpetrator-victim” scenario, in which an environmental hazard is forced upon a powerless nonwhite community. This is not always the case. In 1988, a deal was struck to locate an incinerator in an all-Black suburb of Chicago called Robbins. The debate over the Robbins incinerator, which lasted nearly a decade, emerged as a particularly notable incident of environmental racism because of the willingness of Robbins’ Black leadership and residents to accept the plan. Their support was the result of a longstanding history of racialized underdevelopment and political neglect which had left the town destitute and in need of investment of any kind. As a result, I argue that racialized, historical economic inequality and political neglect can incentivize Black communities to perpetuate environmental racism against themselves. I also argue that the Robbins case illuminates the uniqueness of environmental racism as a form of inequality.

INTRODUCTION

The town of Robbins, Illinois may not be one that typically garners much attention. As a small suburb of Chicago, it sits in the proverbial shadow of the much larger city. Robbins, however, boasts an intriguing history: when it was incorporated into Cook County in 1917, it became the first town in the northern United States to be founded and led completely by Black Americans. It has remained an all-Black town throughout the twentieth century and into the beginning of the twenty-first, and came to be known by many Black Chicagoans as an outpost of comfort and safety. As one of the North’s few all-Black towns, it has also been the site of interesting historical events that can shed light on the operation of race in the United States.

In the late 1980s, Robbins became the site of an intense political conflict. The trouble occurred over a not-so-glamorous but nonetheless important subject: an incinerator. A trash disposal company had decided that they would locate their new incinerator in Robbins, a choice which threatened to bring real health threats to the town’s residents. The plan immediately found resistance, including from many people who lived outside of Robbins in areas such as the Southeast Side of Chicago. Despite their best efforts, though, those who protested the incinerator came up against a vexing obstacle: Robbins’s Black mayor, as well as other officials and residents, fully supported the incinerator plan. As it turned out, Robbins was in such dire economic straits at the time that any sort of investment, even in the form of a trash-burning incinerator, was welcomed by many. These dynamics make the Robbins incinerator debate an incredibly powerful case study in environmental racism.

In this paper, I build on the work of sociologist David N. Pellow and geographer Laura Pulido, both of whom have advanced the scholarship on environmental racism. Pellow has argued that scholars have too often portrayed environmental racism as a phenomenon that occurs between a “perpetrator” and a “victim”, wherein one party unilaterally imposes harm on another. In order to fully capture the complexity of environmental racism, he proposes a framework that takes into account the role of history and stratification not only by race but also by class.1 I offer Robbins as an exemplary case study of how environmental racism operates through complex channels as a result of these forces.

Furthermore, Pulido offers a particularly apt theoretical

1 Pellow’s framework is slightly more robust, containing four key points in total. The two others were not as relevant for this paper. See David Naguib Pellow, Garbage Wars: The Struggle for Environmental Justice in Chicago (Cambridge, Mass.: The MIT Press Ltd, 2004), 7.
framing of environmental racism. She argues that industry and manufacturing require “sinks”, places to deposit their waste and pollution. Normally, land, air, or water serve as sinks, but when necessary, “racially devalued bodies” can serve the same role. This occurs, Pulido argues, because they lack capital and are thus unable to contribute to capital accumulation, meaning that industry makes these people useful by appropriating them as the absorbers of their pollution. However, I expand Pulido’s point by arguing that racially devalued people do contribute to capital accumulation, precisely through their role as sinks. This repositions nonwhite bodies as crucial to an economic system that consistently needs to find places to deposit its negative externalities. Through this lens, it becomes clear that environmental racism is deeply connected to racialized economic inequalities.

In what follows, I begin by sketching a brief history of Robbins, illustrating how a town with such a powerful claim to history has run up against countless systemic obstacles because of its racial composition. This provides the backdrop for the discussion on the incinerator debate, which largely revolved around competing claims of environmental harm on one hand, and economic gain on the other. Finally, I argue for three sets of historical and theoretical takeaways from the Robbins narrative: first, environmental racism can, in fact, be upheld and propagated by Black individuals; second, environmental racism in a post-racial U.S. operates not simply through face-value discrimination but more so through economic discrimination that uses race as a medium; and third, the Robbins case shines light on certain elements of the uniqueness of environmental racism as a form of inequality.

THE STORY OF ROBBINS AND THE INCINERATOR DEBATE

When Robbins was founded in 1917, it was expressly meant to become a beacon of Black self-reliance. Its founder, Thomas Keller, explained the spirit behind the founding of the town: “The real way to help colored people is to make it possible for them to help themselves. Give them housing and transportation and they will segregate themselves naturally.” For Keller and Robbins’ residents, being able to help themselves meant establishing entire political structures that would operate autonomously of white society. The beauty of Robbins was that it was a place where Black Americans could “hold their own elections, collect their own taxes, operate their own schools, maintain their own police and fire departments.”

Unfortunately, Robbins’ claim to history would also become one of the main sources of its troubles. Building and operating a racially isolated, Black-led town in the 20th century meant that residents struggled with various issues, such as health problems, lack of investment, and political neglect. In 1938 the Pittsburgh Courier noted that Robbins suffered from “poorly constructed homes” and “a lack of modern plumbing.” The town’s water system presented “the greatest possibility for spread of disease,” and the mayor at the time was attempting to get a drainage system built through the Public Works Administration.

Five years later, in 1943, Robbins was declared as one of two towns in the Chicago metro area with the most endangered water supply, causing cases of typhoid fever. When a flood hit the Chicago area in 1948, one Robbins resident wrote an editorial in The Chicago Defender, lamenting, “Nothing has been done…There are now over 5,000 people living out here with no water to drink, bathe in or for other uses as long as seven or eight days at a time.” In 1954, Chicago was hit with one of the worst rainstorms in its recent history, and Robbins was noted as one of the worst-hit communities.

Poverty and a lack of economic investment were perhaps the most glaring and constant challenges for Robbins. In

“When Robbins was founded in 1917, it was expressly meant to become a beacon of Black self-reliance”

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3 “CHICAGO BOASTS ALL-NEGRO TOWN: Robbins, III, Has Negro Mayor and Board of Trustees-- Town’s Population Is 2500, with 11 Churches,” The Pittsburgh Courier, September 24, 1938.
4 ibid.
5 “Robbins, III. Says:- ‘Give Us Housing And Transportation; We’ll Work Out Own Destiny,’” The Pittsburgh Courier, October 15, 1938.
the late 1960s, the city’s leaders attempted to secure financial help from federal programs, but found themselves unable to compete with better-resourced towns and cities. In 1966, the mayor identified the town’s central problem as its lack of industry. He noted that Robbins largely was made up of low to moderate income residents, most of whom commuted to other areas for work. In other words, Robbins residents owned little to no capital themselves, and the town struggled to attract outside investment to compensate. Mayor Marion Smith, who found himself facing the same issues in the 1970s, did not hesitate to disclose the underlying reason that his town was in such a dire state: “We invite industry to come look us over, but as soon as they see we’re a black village with black leadership, they look the other way.” Outside investors, companies and politicians expressly denied working with Robbins because it was a Black town, denying it the ability to develop true economic and political independence.

This was a systemic issue. Black mayors across Illinois reported that they struggled to attract industry and solicit state assistance. Their towns lacked jobs, with most residents commuting to other locations if they could find employment to being with. Many of these communities, not coincidentally, were also some of the poorest in the state; Robbins in particular ranked last in socioeconomic status according to one urbanologist’s 1975 listing of 201 Chicago suburbs. In 1917, Thomas Keller had imagined that Robbins would become “a thriving Negro center, banks, drug stores, department stores, in fact, a business district on a par with any other community its size in America.” But as hard as Robbins’ leadership and residents tried, they could not overcome the economic consequences that came with being Black in the U.S.

When Irene Brodie was elected mayor in 1989, she inherited these problems. The city had found some relief through community development block grants, becoming one of the largest recipients of the funds in Cook County after 1975. By the late 1980s, however, federal funding for block grants decreased as inflation rose, significantly reducing the amount that Robbins received. The town was eventually cut off completely as a result of evidence of governmental mismanagement before Brodie’s election. Brodie entered office with a debt seven times as large as the town budget. By the time this happened, the town had still not succeeded in attracting major industry. In the absence of government assistance, Mayor Brodie found herself facing pressure to bring any sort of investment or industry to the town.

In her search for ways to economically revitalize Robbins, Brodie felt that she had finally found an answer towards the end of the 1980s. In 1988, Illinois passed the Retail Rate Law, which provided a subsidy for companies to operate incinerators in the state. Attracted by this new legislation, a pair of companies, Reading Energy Co. and Foster Wheeler, began to look for a potential site in Illinois. The companies’ executives quickly found a willing partner in Brodie, who agreed to having their new incinerator built in Robbins. The deal they worked out was ideal for the corporations, which stood to gain $300 million over 20 years. Robbins, in turn, would gain 500 temporary construction jobs, 80 permanent jobs, and at least $750,000 a year in taxes, rent, and fees. These numbers were too appealing for Brodie to resist. Recalling his conversations with Brodie, one Foster Wheeler executive said, “They did more selling to us than we did to them… It was obviously a poor town. I think the leaders just saw that their town was dying and they wanted to do something about it.” Long-standing economic underdevelopment, fueled by racial discrimination, had left Robbins leaders and residents in a position where they would actively bring potential harm to their own bodies if it meant gaining some financial relief.

The plan, however, was immediately met with opposition by environmental justice advocates and residents of the Chicago area who highlighted the dangers of such a toxic facility. After the Illinois Environmental Protection Agency gave the project preliminary approval, 400 residents from the Southwest Side of Chicago protested the prospective construction of the facility. An investigation into the Chicago area’s other incinerators by the Chicago Sun-Times confirmed the dangers that incinerators posed:

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9 “Renewal in Robbins Bogged by Red Tape,” Chicago Tribune, October 6, 1968, sec. S.
10 ”Robbins Mayor Attends Conference in Cleve.,” Call and Post, May 14, 1966.
12 Page, “Question of Confidence: Black Mayor Has Selling Job to Do.”
18 Steinberg, “400 protest health risks of Robbins incinerator.”
contrary to claims that the facility would be harmless, research showed that other incinerators had consistently skirted environmental regulations and had been allowed to continue operating. In a public memorandum, People for Community Recovery (PCR), an environmental justice organization from the Southeast Side of Chicago, protested that these burdens consistently fell on communities of color. Furthermore, PCR and others pointed out that there were alternatives available to handle waste, such as recycling and composting.

Given that many protesters were environmental justice advocates from outside of Robbins, however, the town’s officials continued to press forward with their original plan with the support of many of their residents. At the heart of their counterargument was always the central assertion that the incinerator would be vital for the town’s economic recovery, which overrode any potential harm that would come from it. In a comment lodged at protesters of the facility, Brodie asked, “If incinerators are going to be built, why shouldn’t they be built in a community that needs the income?” At another point, she argued, “There’s always been environmental racism. We’re just making it work for us for once.” These comments reveal a certain resignation, an acknowledgement that though this may not have been the most preferred deal for Robbins, it was the best she felt they could get.

**“Ultimately environmental racism results when economic gain and human welfare are explicitly pitted against each other and the former wins”**

HISTORICAL AND THEORETICAL TAKEAWAYS

The story of Robbins elucidates a few key aspects of environmental racism and how it is produced. First, environmental racism can be supported by Black leaders and citizens themselves, but they are fundamentally still the victims. Mayor Brodie was not a helpless political leader who had an incinerator sited in her town against her will. She actively advocated for this facility. However, her actions were the result of a much broader history of racism that had placed her in position where she felt that supporting environmental racism was the only avenue she had left in order to keep her town alive. In short, racist economic development in the U.S. has created perverse political incentives that can lead Black political leaders to support environmental racism.

Second, in the post-Civil Rights era of colorblind politics, environmental racism occurs not simply because of face-value discrimination but as a result of the interconnections between race and class. For most of the twentieth century, Robbins was denied investment because of explicit racial discrimination. By the late 1980s, this had been made illegal—but the damage had been done. Robbins was an unattractive place to invest not necessarily because companies held racial bias, but more so because past racial bias had given the town high unemployment and a low median income, factors which were simply bad for business. As a result, the only industrial project Robbins could attract was one which other neighborhoods with more choice—choice that they had gained through nonwhite—life. It can, of course, be argued that other forms of economic inequality impact people’s health. But in the case of the Robbins incinerator, the tradeoff of in-

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20 Ibid.
come for health was at the forefront of the public debate. It was a choice of which public officials, corporate executives, and town residents were made painstakingly aware.

**CONCLUSION**

The story of Robbins, Illinois is a powerful one. It was a town founded as a bastion of Black independence. But the racism that the town faced gave rise to a host of systemic problems which plagued it throughout the twentieth century. When the town finally found a project that might save it economically, it came with a dangerous cost: the physical welfare of its own residents. The public debate over the Robbins incinerator and the history that led up to it provide valuable lessons about environmental racism. First, history has the potential to place Black Americans in a position where they perpetuate environmental racism against themselves in an effort to gain economic relief. Second, a supposedly neutral free market without face-value discrimination will nonetheless breed racist outcomes because history has blighted majority-Black areas, making them poor areas to invest in even if officials or executives have no outright racist motives. Third, environmental racism is a particularly pernicious form in inequality because it results from a contest between human life against economic gain where the latter wins.

The Robbins incinerator was ultimately built in 1997, but was shut down three years later after the subsidy that was crucial to its funding was repealed. For years afterward, Robbins courted several other attempts at economic revitalization, all of which involved some measure of environmental disruption to the town. It is as if the incinerator story continues to repeat itself. Unfortunately, if left to the vagaries of the free market, it likely will.

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ABSTRACT

The end of the Vietnam War led to the migration of hundreds of thousands of Vietnamese refugees to the United States after political and economic upheaval. As another result, the refugees’ years of warfare, trauma, death, and injury began to manifest as unprecedented mental health issues that American physicians and researchers sought to understand. In this paper, I argue that American medical professionals—in good faith—operationalized [Vietnamese] culture to help themselves and their colleagues understand the mental health issues of Vietnamese refugees. Yet this operationalization acted as a double-edged sword. Viewing Western mental health discourse through the lens of Vietnamese culture aimed to help experts better understand Vietnamese refugees’ perceptions. But it also acted as a means to exclude, ostracize, and ultimately define the refugee population as the “other.” Through this inclusion of culture as a player in medical and mental health intervention, the psychological treatment of Vietnamese refugees demonstrates a longstanding tension that surrounds the role of culture, tradition, and ethnicity in public health work.

INTRODUCTION

Public health interventionists have struggled to evaluate the role that culture plays in the distribution and evaluation of healthcare services for decades. More often than not, a population’s culture has served as a way to stereotype and define the group as the atypical “other.” This is particularly relevant for vulnerable minority populations. For example, “Puerto Rican syndrome” (otherwise known as ataque nervios or a general, sudden onset of emotional distress) was coined in the latter half of the 20th century, inspired by the increasing Hispanic population in the United States. Patricia Gherovici’s aptly-named historical analysis The Puerto Rican Syndrome argues that the establishment of such a definition obstructed and obliterated Hispanic patients’ personal experiences and cultural references; “Puerto Rican syndrome” and thus Hispanic culture became a way to essentialize differences in terms of nationality and race (Gherovici, 2003). In a similar framework, I wish to examine the role that Vietnamese culture played in [the language of] healthcare in relation to incoming Vietnamese refugees to the United States after the Vietnam War. As these refugees sought political and economic haven after the fall of Saigon in April 1975, the need arose for mental health counseling to address the refugee-related trauma these immigrants experienced, not only in Vietnam but also during their journey to the States. This novel type of treatment demanded a working knowledge and incorporation of Vietnamese culture and tradition into the Western medical dialogue surrounding mental health in hopes of better understanding and treating depression, anxiety, and post-traumatic stress disorders (PTSD)—common conditions with which these refugees struggled. In this paper, I argue that American mental health professionals and researchers operationalized Vietnamese culture in good faith when discussing mental health treatment. I define “operationalizing” culture as applying Vietnamese culture to and viewing it through the lens of Western ideals. Throughout this work, I have framed operationalization as a double-edged sword: On one hand, this application of Vietnamese culture aimed to assist experts in better empathizing and understanding mental illness in Vietnamese refugees. Yet simultaneously, it excluded, ostracized, and ultimately defined the refugee population as the “other,” the atypical. Through this inclusion of a “non-Western” culture into a larger discussion of Western mental health intervention, the psychological treatment of Vietnamese refugees demonstrates a lasting tension that surrounds the role of culture, tradition, and ethnicity in public health work.

1 Before employing the term “culture” throughout my paper, I have defined this term as the collective of customs, traditions, attitudes, beliefs, and nature of interpersonal interactions of a given population. In this case I am considering native Vietnamese culture, and not Vietnamese-American culture, which is still unfolding today.
historical tension surrounding the roles that culture, tradition, and ethnicity play in public health work.

I divide my research into four sections: First, I situate Vietnamese refugees within the context of the chaos of the Vietnam War during the mid-20th century. This lays the foundation to, secondly, discuss the development of mental health programs and clinical research concerning the mental health status of incoming refugees. The next two sections describe the duality of operationalizing culture. I discuss both the progress and pitfalls of mental health professionals, physicians, and researchers while utilizing [Vietnamese] culture in their understanding of mental illness in this specific population. Through this work, I reveal the complexities of effectively incorporating culture into treating populations that may not share a “typical American” background, socioeconomic status, or language. Lastly, I briefly touch upon the present—what the mental health landscape looks like today for the former Vietnamese refugees, the first-generation Vietnamese Americans. Finally, as a daughter of two Vietnamese refugees, alongside academic contributions, I acknowledge that this work has fostered a more intimate and nuanced connection to my ethnic and family history.

WAR, POLITICS, AND MIGRATION: THE JOURNEY TO AMERICA

American interference in Southeast Asian countries, particularly during the Vietnam War, led to the abrupt emergence of Vietnamese immigrants in the United States. The War laid its foundation starting with the French colonization of Vietnam in the mid-19th century. Decades later, the occupying French army was defeated by Ho Chi Minh—a Communist revolutionary leader—and his Viet Minh Front army. This resulted in Vietnamese independence from French Indochina and the formation of two distinct Vietnamese countries: the [Northern] Democratic Republic of Vietnam, led by Ho Chi Minh himself, and the [Southern] Republic of Vietnam led by Ngo Dinh Diem, a prominent Vietnamese politician (“Vietnam War,” 2009). While the Democratic Republic of Vietnam incorporated and enforced a Communist government, the United States wished to quell and contain any instances of international Communism. This led to the States supporting Diem’s Anti-Communist ideals: The United States wished to stifle the potential expansion of Communism to neighboring Southeast Asian countries (Zhou & Bankston III, 2000).

For decades, United States presidents sent military personnel, advisors, wartime weapons, and other resources to assist the Southern Vietnamese government. Yet due to religious factioning and Diem’s inability to unite South Vietnam forces into an organized front, the Viet Cong (i.e. the National Liberation Front, a group of political insurgents and guerrilla fighters) formed, internally opposing the South Vietnamese government. The Viet Cong weakened, and ultimately overthrew, Diem in 1963, prompting then president Lyndon B. Johnson to send more ground troops in 1965 to avoid the complete collapse of the Southern Republic. But after a series of devastating attacks on South Vietnamese cities and towns (known as the Tet Offensive) in 1968, the United States withdrew American troops in 1973. Unable to defend itself, the South Vietnamese government submitted to the Northern Democratic Republic and relinquished its capital, Saigon, in late April 1975.2

Surrounding the days before the fall of Saigon, Vietnamese refugees were already beginning to organize their evacuation plans. Vietnamese refugee migration was divided into two periods, each with distinct “waves” of refugees arriving, each varying in background, socioeconomic status, and mode of transportation. Period One began in April 1975 and continued throughout 1977; Period Two began in 1978 and continued through the 1980s. Period One consisted of three primary waves of refugees; their evacuation was made possible by the American enactment of “Operation Frequent Wind,” the assisted departure of the most at-risk Vietnamese from the American and Vietnamese military base in Saigon via helicopters and navy vessels (“Operation Frequent Wind: April 29-30, 1975,” 2010). In both of these waves, Vietnamese individuals were relatively well-educated, spoke some English, and came from metropolitan areas. While some could purchase their way out of the country, many were also affiliated or worked with the United States government and military or the South Vietnamese government. These were the populations most vulnerable for capture and “re-education” by the North Vietnamese government.

Though warfare had ceased, reconstruction in Vietnam was precarious with many oppressive, socioeconomic reforms instituted by the Northern Communist leaders. Thus, Vietnam’s dismal state created the second period of refugee migration. Between 700 to 800 thousand

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2 The day when the Southern capital was overthrown, April 30, 1975, is formally known as “the fall of Saigon.”
Vietnamese refugees, known as the “boat people,” sought to escape their country’s economic and political turmoil via hand-made, weakly-constructed boats and vessels starting in 1978. Many of these boats were simply-crafted fishing boats, meant for only two to three people at one time; instead, these vessels often had more than fifteen, even twenty, refugees at a time. These refugees floated at sea aimlessly for days—even weeks—without adequate food, water, protection, or navigation. Given the lack of appropriate provisions, the journey was very deadly: sea pirates often plundered the ships, murdering passengers and enslaving and sexually assaulting women and children; deceased bodies of family members, children, and adults alike, were thrown off of the side of boats if they had died from dehydration or starvation (Do, 1996). Many of these refugees waited for foreign ships to notice their plight or waited until they washed up on the shores of nearby Southeast Asian countries asking for refuge. Given the incredible danger of mass boat departures from between 1978 to 1979, the Orderly Departure Program (ODP) was established between the Socialist Republic of Vietnam and the United Nations High Commission for Refugees in 1979 to establish an international effort with more than forty countries ready to receive these refugees (International Catholic Migration Commission). This program lasted until 1997. Though many of these refugees would first have to stop in a refugee processing center in the Philippines or Thailand, other countries such as the United States, Canada, Australia, France, and Germany would become their permanent homes. I limit the scope of this research to the work done in the United States, though other countries may have invested in similar efforts as well.

**VIETNAMESE MENTAL HEALTH AND TREATMENT DEVELOPMENT**

Vietnamese refugees began to resettle at the refugee camps crafted out of existing military base camps, such as Camp Pendleton in California and Fort Chaffee in Arkansas. Though emergency medical services and immediate physical needs were prioritized (e.g. treatment for infectious diseases such as tuberculosis or malaria, warm clothing, food, water, and shelter), mental health services gradually became more well-known and made more available, particularly at Camp Pendleton (see page 9). Psychiatrists, mental health workers, and other professionals hypothesized that these illnesses were the result of many traumatic life events in a relatively short period: many refugees experienced the death and/or abandonment of loved ones and family members, the abandonment of their home town, region, and country, the abandonment of familiar traditions, customs, food, and clothing (International Catholic Migration Commission). Many refugees also experienced homesickness, loneliness, and a general disconnect from the unfamiliar people and the foreign environment around them. It also did not help that, overall, Vietnamese culture treated any form of mental illness as very taboo. “Emotional disturbances” could not be shared with others outside of the family households including medical professionals: mental deviations often had spiritual or religious solutions to excise maddening spirits or ghosts (Schultz, 1982). Mental illnesses were also often somatized—appearing as fixable, more-accepted physical ailments (i.e. persistent feelings of malaise would be attributed to a “weak nervous system” or a “weak kidney” instead of a neurochemical or psychological cause) (Muecke, 1983). This psycho-somatization was also referred to as “refugee syndrome” in the 1985 book “Cross Cultural Caring: A Handbook for Health Care Professionals in Hawaii,” published by the School of Medicine in Honolulu, Hawaii. Though not necessarily recognized by the Vietnamese refugees themselves, many American/Western medical professionals noted that this “syndrome” was distinctive among the Indochinese refugees as well as Cuban refugees who relocated to the US mainland several decades before (Palafox & Warren, 1980).^{3} Met with these differences, there was an increase in research to discover the most effective and meaningful means of mental health care for this population. For instance, as refugees relocated into the greater Seattle area, two local community service agencies, the Employment Opportunity Center (EOC) and the Asian Counseling and Referral Services (ACRS) proposed a program called Project Pioneer (Lin, Tazuma, & Masuda, 1979). This program not only offered English courses and counseling to “ease [the] transition of the Vietnamese into American life and helping them find employment,” but also distributed clinical questionnaires to document the physical and mental health status of refugees in the “different stages of adaptation” (Lin et al., 1979). Dr. J.D. Kenzie of the Oregon Health

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^{3}I note here that though all Vietnamese refugees experienced the isolation and unfamiliarity, those who struggled the most with traumatic events such as death, disease, starvation were the “boat people”—refugees from the second period of mass migration. I provide an example in the next section of how the initial period refugees often assisted latter waves of refugees in mental health treatments.
Science University Clinic and the founder of the Indochinese gradually developed the Vietnamese Depression Scale to gauge clinical depression in refugees in a linguistically compatible way. And though there is very little feedback on how well these surveys conveyed language, emotion, and familiarity, common treatments for mental illnesses often included therapy and counseling. Oftentimes, refugees would meet with a counselor and/or mental health professional along with a translator; more uniquely, some clinics also offered group therapy in a way that shifted the focus of the session on achieving distinct goals (i.e. self-reflecting, learning English greetings and conversational phrases, socializing with others) rather than strictly changing mental states or emotions (Kinzie et al., 1988). In tandem, practitioners also prescribed psychotropic medication as needed.

I note that the focus of this work is not necessarily to discuss the detailed inner-workings of the mental health treatments and assessments; it is to examine the discourse amongst experts of health and wellness and how those experts operationalized Vietnamese culture in their conclusions regarding Vietnamese refugees and their health. But providing this context is crucial to understanding what was available at the time. These treatments were, and are, not considered perfect, but instead continuously developing.

CULTIVATING CULTURAL EMPATHY AND UNDERSTANDING

The flux of Vietnamese refugees entering the United States naturally produced mixed reactions from American citizens. Some expressed sympathy while others expressed disdain for their new neighbors. Americans attributed these reactions to cultural difference: these refugees simply did not know the typical ways of American life. Los Angeles Times writer Tracy Wood demonstrated the variety of reactions toward the refugees in context of the “Great Santa Ana Squid Stink”:

Following their own customs, the Vietnamese hung the catch [of squid] out to dry—on every available foot of fence in their Santa Ana neighborhood… Americans with some knowledge of Vietnamese customs acted quickly, telling the Vietnamese ‘you just don’t do that here…” To one policeman it proved what he had known all along: Vietnamese are dirty, different, and don’t belong here… To another police officer on the same force, the incident was a humorous but unfortunately cultural lapse…(Wood, 1978)

To some American citizens, events like that reaffirmed their prejudices against Vietnamese folks. To others, this incident was a mistake, something that could be adjusted through education of American customs. Throughout her article, Wood demonstrates the tension that surrounded the Vietnamese reputation: one of praise for the (primarily economic) adjustments that the Vietnamese population had made, yet one of scorn for the cultural and social progress that was yet to be made. While the average American citizen struggled with their sentiments toward Vietnamese culture, in this section, I argue that culture was operationalized with good intentions and with partial success by American mental health professionals in their mental health care interventions and discourse. These professionals utilized culture (and cultural experts) to assist in better understanding and sympathizing with the refugees and their traumatic experiences. The incorporation of Vietnamese culture also made these professionals more sensitive to the inadequacies of pre-existing “American” mental health treatment. This sensitivity helped to promote efforts to appropriately adjust such treatment.

One way that mental health professionals demonstrated this discretion was by encouraging the employment of Vietnamese counselors, therapists, and social workers—those who were often refugees from the very first waves of migration. For example, the psychological research of Jacquelyn Flaskerud and Nguyen Thi Anh determined the mental health status of Vietnamese refugees at two Los Angeles County mental health centers. These researchers then drew their conclusions based on records of psychiatric patients treated at the center and interviews conducted with choice “informants” such as clinical or administrative personnel who worked intimately with refugees regularly. Flaskerud and Nguyen concluded that the primary aspect of services that were “given priority by the informants included culturally relevant mental health counseling…” that there was a need for “bicultural, bilingual mental health workers or cultural and language interpreters” (Flaskerud & Anh, 1988). The authors demonstrated professionals actively acknowledged the inadequacies of the American mental health treatment at the time. Besides identifying other issues that refugees faced such as the need for financial assistance for housing or the need for more vocational training, these informants ultimately identified the need for more individualized treatment for the refugee population. They wanted to make care more effective. These
demands came to fruition with the active and conscious inclusion of Vietnamese authority figures; there was gradual incorporation of Vietnamese professionals into healthcare leadership positions. These professionals were allowed to speak and contribute to the dialogue surrounding mental health, especially in newspaper publications. Writers of The Washington Post Ronald D. White and Jane Freundel included the voice of Dr. Tran Minh Tung, a psychiatrist at the George Washington United Medical Center. Dr. Tung commented on the attitude toward mental health care in Vietnamese culture:

“Our [Vietnamese] culture has taught us to avoid our emotions, to look upon psychological need as a weakness. Yet the emotions must be released. There is no equivalent to the psychiatrist or the psychologist in Indochinese society… the face that it is considered a weakness for a person to seek emotional help, they have a tendency to hold it all inside. (Freundel, 1979)

Readers were also able to hear the expertise of non-physician Vietnamese voices, such as Jackie Bong Wright, a mental health paraprofessional and former refugee. Wright commented on the migration and the resulting “culture shock” experienced by Vietnamese refugees: “The first wave of refugees in 1975 had worked closely with Americans and spoke fluent English. They could more easily adapt to American life. But that has changed. These [refugees] speak no English, have ever seen a toilet or a street light. The culture shock is amazing” (Freundel, 1979). Wright was able to use her experiences to hold weekly support groups with other Indochinese paraprofessionals for incoming refugees dealing with newly-formed trauma in the Washington D.C. and Virginia areas. Finally, the distribution of power was present even in the leadership positions of mental health services, particularly in Camp Pendleton with the establishment of the “Crisis Clinic” in June 1975. This clinic accommodated psychiatric emergencies. The Pendleton administration decided to make the head of the clinic a Vietnamese physician that had served as the head of the Department of Psychological Medicine at Minh Duc Medical School in Saigon, Vietnam (Richard & Rahe, 1978). The administration offered to sponsor this physician to carry on with his clinical work even after the camp was disbanded. Regrettably, the physician’s name was not mentioned. Through these three examples of inclusion, the presence of Vietnamese authority in academic discourse was clear. These voices, opinions, and medical observations were taken as a public fact, enough for not only for other professionals but for the broader communities that viewed such media coverage.

Another way that the mental health care community incorporated Vietnamese culture in a meaningful and impactful way was through the active acknowledgment and respect of Vietnamese customs and ethnic tradition in academic literature. This was revealed in Imogene C. Brower’s journal article “Counseling Vietnamese,” an analysis of the relationship between the certain cultural behaviors of Vietnamese refugees and their effects on the relationship between these refugees and their counselors. Brower pointedly called for more discretion and sensitivity from mental health professionals, asking counselors to “check their personal feelings about [their] clients, particularly because of the residues of strong and deeply divided emotions that the United States involvement in the Vietnam War created in American public opinion,” where emotions have ranged from “contempt and antagonism to guilt and deep sympathy” (Brower, 1980). Brower emphasized the importance of keeping personal emotions at bay to ensure that the focus was on building the counselor-patient relationship. To achieve a successful counselor-patient relationship, Brower predicted that mental health counseling and therapy would need to be more relatable to Vietnamese clientele. By focusing on topics such as the proper structure and pronunciation of a Vietnamese name, potential communication barriers, and the hierarchal framework of a Vietnamese family,
Brower actively encouraged anyone that interacted with Vietnamese refugees to be more aware, sensitive, and respectful toward these differences.

THE “OTHER:” VIETNAMESE REFUGEES, AMERICAN STANDARDS

Despite the well-meaning intentions and progress toward the respectful and productive discussion and utilization of Vietnamese culture, culture has also been operationalized in ways that have ultimately disadvantaged the refugee population. Incorporating Vietnamese culture into mental health treatment has also excluded refugees from American society. One of the ways that culture was operationalized to “other” Vietnamese refugees was through the construction of culture as a tool to establish hierarchy and as a marker of societal success or failure: Vietnamese culture was ultimately considered inferior to American culture. If Vietnamese refugees embraced and embodied American culture, they would have completed a successful transition, and if they did not, they were considered outcasts, unsuccessful, and unwelcome. Vietnamese psychotherapist Kim Danh Cook commented on the adjustment process in a newspaper article published in The Washington Post: “There’s a certain level of cultural adjustment disorder that is sometimes so severe [that the patients] are being mislabeled as paranoid or schizophrenic” (Murphy, 1985).

This comment was problematic in multiple ways, but firstly, in the way that Cook labeled the struggle to adapt to an entirely new environment a “disorder.” By calling an inherently difficult and stressful refugee experience a “disorder,” Cook pathologized Vietnamese culture as something inherently disadvantageous to success in an American lifestyle. Vietnamese culture was an obstacle that needed to be overcome. By describing the way that other mental health professionals labeled this experience of adjustment in terms of paranoia and schizophrenia, Cook revealed how many mental health professionals, despite their expertise, were still ill-prepared to deal with the experiences of a Vietnamese refugee. Although refugees did have difficulties adjusting to new environments, new foods, and new practices, their experiences may not have always warranted a mental health diagnosis; mental health professionals pathologized struggle.

This concept was further demonstrated in the research study performed by Lin et al, “Adaptational Problems of Vietnamese Refugees,” where the Cornell Medical Index (CMI) was employed to gauge Vietnamese refugee mental health status. “Successful adaptation” was defined in their analysis: “Success in adapting to a new environment invariably involves losing old attachments and gaining new identities” (Lin et al., 1979). One can presume that in this context, the “old attachment” was Vietnamese culture, while the “new identity” to be embodied was a primarily “American” identity. This publication propagated the concept of a cultural hierarchy, where success was gauged on “how American” a refugee could be. There was no comprehensible compromise between the two cultures to achieve this success, as one was inevitably more acceptable than the other in this case.

Despite her recommendations for cultural sensitivity in the previous segment, Imogen Brower also contributed to this cultural dichotomy in “Counseling Vietnamese” by recommending that counselors “instruct the student in acceptable and unacceptable American social behavior, because adhering to social expectations enhanced acceptance and adjustment” (Brower, 1980). Given this context, it is reasonable to assume that Brower meant “Vietnamese behaviors,” in particular, were considered “unacceptable American social behavior.” Brower may have been correct in saying that if Vietnamese refugees adhered to “American social behavior,” they would be more accepted by their neighboring American citizens. Yet by making that recommendation, she ultimately endorsed the adherence to American culture as the only gateway to societal success. Again, there was no compromise possible between these two sets of behaviors.

“Yet by making that recommendation, she ultimately endorsed the adherence to American culture as the only gateway to societal success.”
Culture was operationalized in a way that fostered not only social segregation but also geographical segregation between Vietnamese refugees and American citizens; this was contrary to the sentiments of integration and acculturation that were emphasized at the time. This segregation arose from the plans made soon after the fall of Saigon in 1975 to reorganize and relocate refugees to various parts of the United States. Volunteer agencies (known as VOLAGs) were private charitable organizations under contract to the United States government responsible for creating small concentrations of Vietnamese refugees throughout the country; VOLAG officials believed that refugees would fare better if they had a smaller social network for mutual support and assistance (Zhou & Bankston III, 2000). According to Zhou and Bankston in “The Experience of Vietnamese Refugee Children in the U.S.,” “scattering Southeast Asian refugees around the country to minimize the impact of resettlement on local communities was an initial policy goal” of these volunteer agencies (Zhou & Bankston III, 2000). There was hesitation to disrupt local American communities with the relocation of these refugees: American citizens’ comfort seemed to be prioritized over the refugees’ integration. These refugees already struggled with a lack of familial support, a lack of an extensive social network, and a lack of general resources, whether those resources were economic, nutritional, emotional, or educational. Lin et al. described these clusters of Vietnamese refugees as “forming conspicuous segments in metropolitan areas [that required] special consideration” (Lin et al., 1979). The description of these refugee populations as “conspicuous” conveyed a punitive connotation. These Vietnamese populations unacceptably stood out like a sore thumb from the typical American landscape and demographic. If Vietnamese refugees had adjusted to the American environment sooner or more seamlessly, they would no longer be considered “conspicuous” compared to their American neighbors, which would thus, negate any need for “special consideration” or efforts to acclimatize.

A NOTE ON TODAY AND CONCLUSION

More than 45 years have passed since the arrival of the very first wave of Vietnamese refugees to the United States; those who were once considered refugees are now considered first-generation Vietnamese Americans. They have given rise to the second and even third generations of Vietnamese Americans. Though much has changed and progressed in terms of mental health advo-
cacy in the 21st century, mental health issues continue to afflict first-generation [elderly] Vietnamese Americans. The Vietnam War and its traumatic effects continue to play a role in the lives of this population. According to a 2008 study conducted by the UC Irvine Center for Health Care Policy, these former refugees continue to suffer from higher rates of mental health problems (Tran, 2008). Psychiatrist Dr. Quyen Ngo-Metzger of the Center, who served as the principal investigator of the survey, stresses, “The message I want to bring across is that the medical community needs to realize that Vietnamese Americans are a high-risk group. I hope people realize that mental health is still a problem and not to view all Vietnamese as doing really great” (Tran, 2008). Coupled with the fact that 90% of Vietnamese American seniors have limited English proficiency and that 40% of Vietnamese American households are linguistically isolated (i.e. do not speak English or speak very sparse English), there exist barriers that prevent those from receiving the care that they need (Kandil, 2020).

Though, again, discussion regarding the efficacy of the “culturally-considerate” mental health treatments is outside of the scope of this research, we can understand that the initial operationalization of Vietnamese culture into mental health discourse has not been the most effective nor long-standing decades after its genesis. Work is still being done for this population to this day by Vietnamese Americans.

In conclusion, I showed that culture was operationalized by mental health professionals with well-meaning intentions: by considering Vietnamese culture when researching the mental health needs and status of Vietnamese refugees, health care providers operationalized culture as a means of mobilizing Vietnamese leadership and fostering sensitivity to better understand and treat Vietnamese patients. Despite this progress, culture was also operationalized in a way that disadvantaged, excluded, isolated, and defined Vietnamese refugees as the “other.” This particular study of the mental health treatment of Vietnamese refugees demonstrated that incorporating culture into health care and public health intervention and discourse was and still is difficult. There is progress still to be made to operationalize culture in a way that does not outcast one population from another.

4 There have been valiant efforts to make mental health resources more widely available to Vietnamese Americans in general—not only first generation—especially in places with large Vietnamese populations such as Southern California. For example, the Orange County Association for Vietnamese Mental Health Awareness and Support was formed in 2007 to provide mental health programs for children, youth, adults of all ages and families.
It is difficult to suggest concrete solutions to determine what is the most appropriate way to utilize culture in health care. But what I have found is that the language, tone, and attitude that is used when discussing culture is crucial—all of these factors contribute to the way that a certain population’s customs and traditions are distributed to and conveyed by the broader public. It is disheartening to see that the mental illnesses of the Vietnamese refugees that immigrated to the United States over 30 years ago have not been and may not be completely healed any time soon. Public and/or mental health services have not yet deciphered the most appropriate way to operationalize culture to reach those who are suffering. But as I have shown, progress is not linear: for every two steps forward in the right direction, there may be one step backward. Yet the fact that there is progress at all is encouraging. Through my research, I have also conveyed that there is optimism for the future, that there can be some faith in the work that can be done that will inspire future mental health professionals and public health interventionists for generations to come.

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Resisting Gentrification: Everyday Politics & Collective Action From Oakland to Madrid

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ABSTRACT

This paper utilizes case studies in resistance to housing insecurity and neoliberalism to demonstrate the successful combinations of everyday resistance with collective action. Presenting the case studies as illustrations of two modes of analysis (Feminist Everyday International Political Economy and Marxism) previously thought of as somewhat contradictory, this paper argues that these models can strengthen one another. Using the examples of the Moms 4 Housing movement to resist gentrification and affordability crisis in Oakland, CA, and the Plataforma de Afectados por la Hipoteca (PAH) that followed the Spanish housing and eviction crises, this paper addresses the possibility to combine the structural with the everyday. Attention is called to everyday, visual representations of gentrification through popular culture and “gentrification architecture.” Ultimately, this paper presents exciting possibilities for combining everyday politics with structural approaches to build effective collective action from the bottom-up.

INTRODUCTION

In the winter of 2020, hundreds of protestors gathered around a small house on Magnolia Street in West Oakland, California. The Alameda County Sheriff’s Office deployed militarized tanks and riot gear to surround the crowd. Deputies broke down the door of the home with battering rams and AR-15s. Several minutes later, they emerged with two women, Tolani King and Misty Cross, in handcuffs. King and Cross were arrested for illegally squatting in a vacant home owned by Wedgewood Properties, a large real estate company in California (Burns 2020). However, they were not acting alone; King and Cross are members of a social movement called Moms 4 Housing, a collective of houseless Black mothers from Oakland fighting back against the rapid gentrification and housing crisis in the San Francisco Bay Area.

The Moms 4 Housing movement is situated within a global pattern of resistance to neoliberal austerity. From Moms 4 Housing to the Plataforma de Afectados por la Hipoteca (PAH) in Spain, housing has emerged as a particular site of struggle against the subjugation of the poor under late capitalism. This form of resistance combines the everyday needs of houseless and housing insecure people with the power of collective action. Situated within contemporary debate between everyday international political economy (EIPE) and structural¹ approaches (i.e. Marxism), this paper argues that the intersectional feminist EIPE² approach does not negate collective organizing against larger structures of oppression; rather, feminist EIPE can situate everyday individual actions within organized resistance. Feminist EIPE and Marxism strengthen one another as modes of analysis, and can better dissect such case studies of successful contestations of neoliberalism.

This paper begins with a literature review of the debate surrounding Marxist analysis and everyday politics. Housing crises and gentrification are explained using Marxist theories on the commodification of land and accumulation by dispossession. The everyday impacts of gentrification and austerity are explored through the overlapping lenses of feminist EIPE and Marxism, with particular focus on

¹ What I refer to as ‘structural’ is also known as ‘regulatory international political economy,’ which Hobson & Seabrooke (2010) argue includes both neoliberal analyses asking “Who governs?” and Marxists or world systems theorists asking “Who rules/benefits?” Hobson & Seabrooke (2010) assert that while both of these modes of analyses reach different conclusions, their approaches both lack the ability to address the everyday lives of the people impacted by such regimes, nor the bottom-up agency that these ordinary people may possess (pp. 291-193).
² Throughout this paper, I refer to this mode of analysis as “feminist EIPE,” although its commitments to intersectionality should not be underestimated.
architecture and popular culture. Finally, global examples of individual and organized resistance to gentrification and its implications for the debate between feminist EIPE and more structural approaches are discussed.

LITERATURE REVIEW

Recent developments in political science have opened up new avenues for conceptualizing politics through the everyday. Everyday international political economy (EIPE) argues that it is not enough to focus on top-down, regulatory regimes when the impact of said regimes and resistance against them can be found in everyday life. EIPE has often placed itself in opposition to the structural approaches that EIPE pioneers Hobson & Seabrooke refer to as regulatory international political economy, which includes both neoliberal statecraft models and Marxism (2010). The purpose of EIPE, Hobson & Seabrooke argue, is:

neither to marginalise the importance of the dominant elites nor to reify the agency of the ‘weak’, but rather to analyse the ways in which the weak affect and respond to the dominant and how in the process this interactive relationship generates change in the global economy. (2007, p. 2)

Alongside the recent mainstreaming of the everyday in political science, feminist scholars argue that EIPE must also recognize the longstanding feminist tradition of focusing on the banal (Elias & Roberts 2016). The second wave feminist slogan “the personal is political” predates the everyday politics shift of the 2000s by several decades (Hanisch 1969). Cynthia Enloe’s feminist, multidimensional retheorization of power in the 1990s brought gender and race from the margins of political economics to the core (Enloe 1990). Enloe, a key player in the eventual development of feminist EIPE, argued that structural approaches to political economy either neglect everyday life entirely, or study everyday life but do not view it as powerful enough to impact politics on a grand scale (Enloe 2004, p. 24).

Feminist EIPE, however, argues that everyday actions are more than capable of shaping politics from the bottom-up. Feminist EIPE further highlights the ‘feminization of resistance’ — “the increase in more individualized forms of resistance within certain workplaces … where women make up the majority of workers” (Redden 2016, p. 847, Ustubici 2009). Scholars in this field pay particular attention to centralizing the individual voice and agency of those on the margins, arguing that social reproductive labor is inseparable from capitalist modes of production. Thus, analysis of capitalist regimes must acknowledge the gendered and racialized social reproduction behind them. They can do so by following the lead of feminist scholars who have long focused on the mundanities of everyday life, “asserting the need to uncover the micro level processes through which these transformations take shape” (Elias & Rai 2018, p. 202).

Moreover, the EIPE approach and Marxism hold apparent contradictions, not only in their theories but also in the different avenues for resistance that they offer. The EIPE model focuses on individualized, everyday actions; feminist EIPE goes further, suggesting that small acts of daily rebellion should be acknowledged as legitimate forms of resistance within the gendered and racialized opportunity structure for resistance. This prompts problems for Marxists, including Marxist-feminists, whose systemic analysis of oppression under capitalism demands a systemic approach to resistance, mainly through labor unionism, strikes, and large-scale revolutionary aims. The feminist EIPE critique of Marxism, however, overlooks that Marxists themselves have highlighted the need for bottom-up organizing models that reassert the agency of the oppressed in their own collective liberation (McAlevey 2016, Friere 1970). This paper interrogates whether or not these contradictions are irreconcilable. Utilizing the case studies of collective resistance to housing crises, this paper argues that feminist EIPE and Marxism can strengthen rather than invalidate one another.

HOUSING IN CRISIS: EVICTIONS AND GENTRIFICATION

To understand resistance through both everyday and collective action, we must first understand the current state of housing and gentrification that makes such resistance necessary. Many argue that various housing crises through history have been the result of poor public policy or exceptional greed; however, the root causes of housing crises, such as the 2008 housing bubble and the contemporary affordability crises, can be instead explained by the inherent contradictions of capitalist commodification of housing. Socialist economist Karl Polanyi (1944) argued in The Great Transformation that capitalism creates “fictitious commodities” out of land. Fictitious commodification, Polanyi (1944) argued, creates conflict between society and markets; the resistance of the houseless and housing insecure to urban austerity and affordability crises demonstrates the inevitable class struggle when com-
Building on Polanyi, Marxist geographer David Harvey claimed that a central tenet of the contemporary housing crisis is the shift of housing from use-value to exchange value. Applying his theory of accumulation by dispossession¹ to the financialization of the housing market, Harvey (2019) asserted that “large segments of the economy are being run on the accumulation of capital, which is not involved in producing anything. It’s all about the trading of asset values” (6:41). In other words, financialization of the housing market is integral to the production of a housing crisis. When large real estate companies purchase properties only to incur value, not to be used for housing, a housing crisis follows. At the most profitable point in Bay Area housing market history, there remained nearly 2,000 more vacant homes than unhoused people in the city of Oakland (Kawamoto 2020, Carlisle 2020). For investors and real estate companies, the Bay Area housing market is thriving; for working people in search of housing, the market is unlivable.

Housing crises are not symptoms of diseased or broken housing markets. Rather, the fundamental tenets of a commodified housing market are the very qualities that cause housing crises in the first place. Describing the United Kingdom’s privatization of public housing in the 1970s, David Harvey recounts that:

[Housing] speculation took over, particularly in prime central locations, eventually ... forcing low-income populations out to the periphery [sic], and turning erstwhile working-class housing estates into centres of intense gentrification. The loss of affordable housing produced homelessness and social anomie in many urban neighbourhoods. (Harvey 2018, p. 158)

Additionally, gentrification and houselessness are deeply racialized and gendered issues, as austerity impacts are disproportionately felt by women of color (Kandaswamy 2018). Approximately 60% of unhoused families in the United States are single-mother households (Bhattacharya 2020). In California, where the total population is 6.5% Black, Black people make up 40% of the houseless (Bhattacharya 2020). The Black population in Oakland, which once stood at nearly 50% in 1980, dwindled to only 28% in 2010 and is expected to reach as low as 16% in the next several years, as more Black residents leave the Bay Area in search of affordable locations (Levin 2018).

**GENTRIFICATION IN THE EVERYDAY**

Though gentrification may be caused by structural issues, feminist EIPÉ allows us to analyze how the impacts of such patterns are felt in everyday life. Particular attention has been called to the visual markers of gentrification. Specifically, the contemporary architectural brand of boxy, neutral-toned buildings has become so associated with rapid demographic shifts in neighborhoods that it is colloquially known as “gentrification architecture.” Gentrification architecture exemplifies the everyday politics of placemaking in urban areas. Specifically, the nondescript, minimalist architecture of gentrification seeks to visually neutralize the history of displaced communities. The ahistoricism of gentrification architecture erases the history of politicized spaces, such as West Oakland, a stronghold for the Black Panther Party in the 1970s. This placemaking of gentrification upholds whiteness in physical spaces, but “for the collective memory of space to be reconstituted, there needs to be a mutual forgetting of what came before the constructions of new buildings, restaurants, and businesses.” (Opilllard 2015, pp. 6-7). Further, “urban renewal” programs merely mask the inequalities perpetuated by gentrification and capitalist development without ameliorating the inequality itself (Fincher et al. 2016). In so doing, gentrification architecture also embodies Marxist commodity fetishism⁴ (Marx 1867).

Popular culture emanating from rapidly gentrifying areas reveals local analysis and resistance to gentrification in the everyday. A recent proliferation of films from the San Francisco Bay Area, including Boots Riley’s *Sorry to Bother You* (2018), Carlos Lopez Estrada’s *Blindspotting* (2018), and Joe Talbot’s *The Last Black Man in San Francisco* (2019), all feature gentrification as central themes. In *Blindspotting*, the house of a Bay Area “transplant” is visually marked by gentrification architecture. All of these films benefit from both feminist EIPÉ and Marxist analysis, the latter of which comes through particularly strong in Boots Riley’s *Sorry to Bother You* (2018). The films use the narrative storytelling devices of interpersonal relationships to demonstrate the everyday, lived realities of

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¹ “Accumulation by dispossession” refers to David Harvey’s theory that neoliberal capitalism centralizes wealth and power in the hands of a select few by forcibly dispossessing the working class through mass privatization of land and public goods (Harvey 2007). It is an expansion of Karl Marx’s theory of primitive accumulation.

⁴ “Commodity fetishism” refers to the process through which capitalism masks the labor and use values of commodities, making the exchange value of commodities appear to be magically severed from the labor-time required to produce them (Marx 1867).
gentrification and austerity—what Hall (2019) refers to as “mundane mobilities,” wherein “austere conditions [sic] limit where and with whom people can live near, move to or even move away from” (p. 782).

The Last Black Man in San Francisco (2019) visually highlights the antithesis to gentrification architecture—the historic Victorian homes of San Francisco (Talbot). The film describes a young Black man’s hyperfixation on the design and upkeep of his childhood home, a mechanism through which the audience understands both the cultural, political, and personal significance of the house. When the main character reclaims the home by squatting in it during its vacancy, viewers not only believe he is justified but read his reclamation of the home as an act of justice.

Feminist EIPES makes room for the intimate forms of resistance displayed in The Last Black Man in San Francisco, from the main character Jimmie’s squatting in his childhood home to the gendered and racialized vulnerability shared between Jimmie and his best friend (Talbot 2019). Through the lens of feminist EIPES, the effects of housing crises on interpersonal relationships can be just as important to understanding the political economy of gentrification as understanding housing commodification and profiteering. Viewing Marxism and feminist EIPES not as contradictory modes of analysis but as overlapping ones can help identify how local productions of knowledge via pop culture reflect both the structural and the everyday.

MODES OF RESISTANCE: RECONCILING THE EVERYDAY WITH COLLECTIVE ACTION

Squatting has become an essential form of resistance against housing crises in reality. By focusing specifically on the intersectional dimensions of urban squatting, we can address the “invisibility of women in the urban space … enabling us to focus on their agency and thereby helping to disclose prevailing power relations in society” (Wittger 2017, p. 18). However, the feminist EIPES approach alone is insufficient to explain successfully organized resistance against housing austerity. This section utilizes two prominent cases that combine the everyday resistance of squatting with collective action: Moms 4 Housing in Oakland and the Plataforma de Afectados por la Hipoteca (PAH), a social movement in Spain that utilizes organized civil disobedience in the form of squatting to fight for fair housing and against the profiteering of the housing market (Berglund n.d.).

When Moms 4 Housing first gained national media attention, Wedgewood Properties refused to negotiate with the mothers so long as they continued to illegally “squat” in the long-vacant residence. Support for the mothers grew through viral, informal videos expressing the disparity between the cost of rent in Oakland—a “housing wage” estimated at $33 per hour—and the current minimum wage of $15. “Before we found each other, we felt alone in this struggle,” reads the Moms 4 Housing website. “But there are thousands of others like us here in Oakland and all across the Bay Area. We are coming together with the ultimate goal of reclaiming housing for the community from speculators and profiteers” (para. 2, n.d.). The message embodies the need to move beyond action in isolation and towards collective action.

The Moms 4 Housing movement centers around Black women, who are often pushed to the margins even in movements contingent on their labor. In the case of Moms 4 Housing, Black mothers and their children are the faces of the movement, employing personal storytelling and vulnerability to appeal to their audience’s emotions. Feminist EIPES’s politicization of the body, specifically for women of color, reconstructs the mothers’ squatting to fulfill their unmet need for physical shelter as a form of resistance in and of itself. “Politicalising the body by making it a site for resistance,” Ustubici (2009) argues, “challenges ideological and historical processes that exclude bodily experiences and activities from political discourse” (p. 29). Yet Marxist analysis of collective action is also critical in understanding the results of the Moms 4 Housing movement: Wedgewood Properties ultimately agreed to sell the house to a non-profit organization for affordable housing. Feminist EIPES and Marxist analysis in conjunction can aptly understand how Moms 4 Housing successfully combined individualized squatting with community power to achieve a significant win in the fight against capital and housing insecurity.

Another example of squatting and collective resistance is Plataforma de Afectados por la Hipoteca (PAH), a coalition that resists the financialization of the housing market that left hundreds of thousands houseless and debt-ridden. During the Spanish speculative housing bubble prior to the 2008 recession, nearly 80% of the population were homeowners, but many of them were low-income workers with subprime mortgages (Berglund n.d.). Half a million people who were evicted from their homes still carried debt into their evictions (Berglund n.d.). Blackstone and
other private-equity giants took advantage of the housing crisis to buy up properties at low costs, turning many of them into rentals (Berglund 2018). This pattern was seen across the world following the 2008 recession; in fact, the mass purchasing of foreclosed homes from companies like Blackstone led in part to the housing crisis seen today in Oakland, CA.

While the PAH remains local and situated in the everyday, its success comes in large part from its rejection of neoliberal individualism in favor of collective action (Di Felicianantonio 2017). The abandonment of squatting as a form of satisfying individual needs allows PAH to turn instead toward the needs of the community. “The action of the PAH is aimed at giving a concrete solution to the housing problems of the people involved, not at creating an oppositional dialectics with capitalistic institutions. It could be better said that these political horizons coexist” (Di Felicianantonio 2017, p. 52). PAH exists as part of the “politics of possibilities,” a theory shared by feminist EIPE modes of resistance that critically engage with resistance as it becomes available to the oppressed (Di Felicianantonio 2017, Enloe 2011, Elias 2019).

CONCLUSION

There are several important limitations to the organizing models of Moms 4 Housing and PAH. Though PAH is often lauded as a success, it was not without its flaws, including the government passage of anti-civil disobedience legislation and minimal to no comprehensive housing legislation (Martinez 2017). The initial process of organizing for collective action around housing is similarly challenging, as many feel ashamed of their positions and afraid of contentious collective action (Santos 2018). On the other hand, overcoming organizing challenges sets an important precedent for conceptualizing resistance in the future. Santos identifies that the key was solidarity (2018). By presenting a new mode of analysis centering solidarity, not only can we better understand social movements, but we can better shape them as well (Santos 2018).

The displacement of working-class people from their homes is both a product of capitalism and a key component in capitalist reproduction. Disrupting this displacement from the bottom-up is a significant form of anti-capitalist resistance that successfully secures material gains for those impacted by gentrification and the financialization of the housing market. The case studies of Moms 4 Housing and PAH demonstrate how the intersectional feminist EIPE approach makes room for a multidimensional understanding of resistance (Enloe 2011, Elias 2017). These examples of resistance serve as a model for reconciling individual action in the everyday with the need for collective action to address the structural problems that plague everyday politics in the first place. They support the argument that feminist EIPE and structural Marxist approaches can uplift, not contradict one another. When everyday resistance as it stands—gendered, racialized, and often unrecognized as a legitimate form of resistance—is combined with collective action, agency is returned to the hands of the oppressed in contesting power from the bottom-up.

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ABSTRACT

This paper studies the gender gap in academic achievement using a nationally representative survey of middle school students in China. Chinese girls outperform boys in Mathematics, Chinese, and English by 13.5%, 62.1%, and 61.5% of a standard deviation, respectively, which is one of the largest gender gaps in the world. Using the OLS regression with interactions between gender and family-, teacher-, and school-level variables, I show that girls benefit from having a same-sex teacher in Mathematics and Chinese. For boys, however, the effect of sex congruence with the subject teacher is insignificant in all three subjects. Girls’ resilience in the face of adverse family and school environments also contributes to the gap. In dysfunctional families and lower-ranking schools, the female advantage is even more pronounced.

INTRODUCTION

The gender gap in academic performance is an important and prevalent problem around the globe and throughout the education process. In most countries, girls consistently underperform boys in Math, while boys fall short in Reading subjects (Klecker 2005). Researchers have found that gender gaps in Math and Reading emerge as early as in primary school (Golsteyn and Schils 2014; Fryer and Levitt 2010) and persist through middle school and high school (Bharadwaj et al. 2012). The gender gap in test scores can also translate into gendered educational and career choice in college and beyond (Maple and Stage 1991; Jacobs 2005), which arguably accounts for a significant share of the gender gap in earnings from employment (OECD 2016).

Past research has investigated a wide range of mechanisms to explain the Math and Reading gender gap but finds conflicting evidence. Some scholars have argued that a higher degree of gender equality in the country is related to a smaller or even reversed gender gap in Math (Guiso et al. 2008), while more recent studies refute this relationship (Fryer and Levitt 2010; Stoet and Geary 2013). Among other factors, studies have pointed out that gender congruence with teacher has a substantial impact on students’ performance (Dec 2007; Lim and Meer 2016); however, Bharadwaj et al. (2012) do not find such evidence.

Despite wide discussion of the academic gender gap in literature, few studies have focused on China — the country with the largest education system in the world — partly due to the lack of publicly available data. Fortunately, this paper is able to use recent data from the China Education Panel Survey (CEPS), the first nationally representative survey of Chinese middle school students, to reveal a striking gender gap in students’ test scores. This paper employs fixed effect Ordinary Least Square (OLS) regression with interactions between gender and environmental factors to explore the heterogeneous impacts of family, classroom, and school environments on boys and girls. The findings suggest that the gender congruence with subject teachers and girls’ resilience in the face of adverse family and school environments might, to a large degree, have contributed to girls’ advantage over boys across all three academic subjects.

This paper contributes to this rich body of literature in two important ways. First, this study reveals a striking “new gender gap” in Chinese middle schools. Contrary to the persisting Math advantage of boys in western countries, Chinese girls actually outperform boys in Math. The female advantage in Chinese and English is also of much greater magnitude than what past literature has found.
Second, previous research using the CEPS data mainly focused on the effect of student-teacher gender congruence on test scores (Gong et al. 2018; Zhang 2019; Chen, Chen & Hu 2019). To the best of my knowledge, this paper is the first using the CEPS data which explains the gender gap from the family and school perspective and shows that girls and boys react differently to adverse family and school environments.

The remainder of the paper is structured as follows. Section 2 describes the data used in the analysis and gives some preliminary observations. Section 3 lays out the model and presents regression results. Section 4 performs robustness checks. Section 5 recapitulates the main findings and concludes the paper.

**DATA**

This paper applies a cross-sectional analysis on the baseline survey of CEPS, which sampled 19,487 students in the school year 2013-14 with a multi-stage sampling design. Among them, 10,279 students were in grade 7 (freshman in middle school, age 13), and 9,208 students were in grade 9 (senior in middle school, age 15). Excluding students who have no test score record, the final sample consists of 19,028 students in 438 classrooms across 112 schools. In order to make inference to the underlying population, this paper incorporates the inverse probability weights in the data which denote the sampling probability of each observation.

Weighted summary statistics are displayed in Table 1. The student outcome variables are the midterm test scores of Math, Chinese, and English. Since the midterm exam was designed individually by each school and different across grades, I standardize the scores within each school-grade level to have mean 70 and standard deviation 10. Note that the test score is still not comparable between schools after the standardization — a strong student in a top school might score below the mean, whereas a weak student in a low-achieving school might have better test scores than the former student after the intra-school standardization. Therefore, regressions on test scores only make sense if we include a school-grade fixed effect to limit the comparisons within the same grade at each school.

Strikingly, girls in the CEPS survey have significantly better performance than boys in all three subjects. Female-male difference in mean scores for Math, Chinese, and English equal 13.5%, 62.1%, and 61.5% of a standard deviation, respectively. Interestingly, despite girls’ significant advantage in Math, girls are more likely to report difficulty in studying Math in grade 6, the year preceding middle school.

One might expect the background variables for boys and girls to be similar since the sex of a child could be seen as randomly distributed across households. However, China is an exception due to its long-standing one-child policy, and researchers have found the impact of the one-child policy to vary across rural and urban divides, eastern and western provinces, and ethnicities. For example, most urban couples had only one child, whereas rural and ethnic minority couples were often allowed to have a second child or more, particularly if the first one was female (Zhang 2017). Moreover, sex-selection technology was somewhat available in urban areas for those with a strong preference for sons.

Given the heterogeneous impact of the one-child policy, it is not surprising to find disparate means for boys and girls in many family variables. Noticeably, boys are more likely to be the only child and reside in well-off households, while girls tend to study in local schools and have both parents at home. At the same time, boys are more likely to face adverse family environments where the father is alcoholic, parents have bad relationships, or parents fight regularly.

Most of the variables are balanced at the classroom and school level, except that girls are more likely to attend public schools at a 5% significance level. The distributions of certain school variables do not appear independent of gender, but no consistent and meaningful pattern can be found. For example, boys are slightly more likely to attend schools that are among the best in the region, whereas they also tend to be in schools that are ranked
We have seen a “reverse gender gap” in Math as well as large female advantages in Chinese and English from the mean scores. Figure 1 shows that boys have a thicker left tail in their Math score distribution which brings down the average score, but boys and girls perform comparably toward the right tail.

In Chinese and English scores, however, the entire distributions of boys are to the left with respect to those of girls (Figure 2 and Figure 3). Table 2 corroborates this pattern by presenting the ratio of boys to girls in the top and bottom percentiles. There are more boys than girls in the bottom 1, 5, and 10 percentiles across all three subjects, with the ratio as high as 6.35 to 1 in Chinese. Girls are also overrepresented in the top percentiles compared to their share in the student population, except for the 99th percentile in Math. Consistent with past literature, there is a slight male advantage in Math among top achievers (Tsui 2007).

MODELS AND RESULTS

This section aims to explore the mechanism of the “new gender gap” using the weighted OLS regression with fixed effects and interactions. The first specification is of the form

$$Y_{ijk} = \beta_0 + \text{Female}_{i} \beta_1 + \text{Female}_{i} \times (\text{school}_{j} \beta_2 + \text{grade}_{k} \beta_3) + \text{sex}_{ij} \beta_4 + \text{school}_{j} \beta_5 + \epsilon_{ijk} \quad (1)$$

where \(i\) indexes students, \(j\) indexes schools, and \(k\) indexes grades. \(Y_{ijk}\) denotes the standardized midterm test score for student \(i\) in grade \(k\) at school \(j\). Female is the indicator variable that equals 1 if student \(i\) is female. \(x_{ijk}\) is a set of individual-, family-, and teacher-level covariates detailed in the summary statistics, and a subset of it, \(x_{ijk}^\text{1}\), is interacted with the female indicator. \(\text{school}_{j}\) denotes a set of school-level variables of school \(j\), and it is also interacted with the student’s gender. \(\text{D}_{jk}\) is a set of school-grade fixed effects to limit the comparison within the same grade at the same school. The standard errors are also clustered at the school-grade level. Table 3 reports the results for Math, Chinese, and English specifications. Due to the large number of covariates in the regression, the full results are displayed in four panels according to the variable categories.

1. Student-level Variables

Table 3 Panel A displays the estimated coefficients of the student-level variables. Students who are the only child in the household score higher in all three subjects compared to students with siblings, and the effect is the largest in English and significant at 0.1% level. The signs of the interaction terms suggest that being the only child helps girls more on Math but boosts Chinese and English scores for boys more. It is surprising that, within the same school-grade, students of rural backgrounds perform 7.2% of a standard deviation better in Math than urban students, while not falling short in Chinese and English as well. Additionally, the CEPS-designed cognitive test appears to be strongly correlated with students’ academic performance. A single standard deviation increase in cognitive score brings up Math scores by 43% of a standard deviation, and Chinese and English scores by slightly smaller magnitudes. Finally, if a student reports difficulty with a subject in grade 6 (the year preceding middle school), the student tends to suffer more in middle school.

2. Family-level Variables

In Panel B, family-level economic status reveals a pattern distinct from most studies — students in “rich” households actually perform worse than students in “medium”
or “poor” groups. Nonetheless, parental education is still strongly correlated with student test scores. If either of the student’s parents holds a bachelor’s degree, the student scores higher in all subjects by over 15% of a standard deviation on average. Moreover, a gendered mechanism seems to be working on the side of parents. A highly educated mother raises Math scores the most, while a college-trained father brings the biggest improvement on other subjects.

As expected, parental absence negatively affects all subjects, while the impact of an absent mother is the most significant. I construct a composite score to measure the degree of the family adversities. The score sums up three dummy variables: “Father drunk,” “Parent fight,” and “Parent in bad relation.” Compared to students who report none of these situations, students reporting any degree of family dysfunction underperform in all subjects.

However, the interaction terms with female indicate that girls suffer relatively less than boys, or perhaps do not suffer at all, in an adverse family environment. All but one interaction term yield positive point estimates, and female students who report all three dysfunction indicators even score higher in Math than the base group, although this group should be interpreted with caution given its small size. This squares with past evidence that girls tend to be more resilient in the face of adverse family environments.

3. Teacher-level Variables

The results from teacher-level variables corroborate past findings that sex congruence with a teacher influences student outcomes. I find that having a female home teacher improves all test scores regardless of students’ gender. The effect can be as great as 20% of a standard deviation for Chinese and is significant at the 1% level after controlling for the home teacher’s teaching experience and qualifications. This seems to suggest that female teachers, on average, are better moderators in the homeroom, which involves dealing with various interpersonal issues that may indirectly impact students’ overall performance.

While the gender of subject teachers has no significant influence on boys’ test scores, girls seem to be uniquely benefiting from having Math and Chinese teachers of the same gender. Female Math and Chinese teachers raise girls’ test scores by 9.43% and 11.46% of a standard deviation relative to that of boys. To put this in perspective, the female-male reverse gender gap in Math is 1.351 (= 70.699-69.348) in the underlying population. Therefore, in classrooms with a female Math teacher, 69.8% (=0.943/1.351) of girls’ advantage in Math can be explained by having a female teacher alone.

4. School-level Variables

Despite the presence of the school-grade fixed effects, the heterogeneous impact of school on boys and girls can still be identified by interacting school characteristics with gender. The interaction term estimates the effect of the regressor on girls relative to the effect on boys. Note that we cannot obtain the point estimates for the school-level variables due to the collinearity with fixed effects used in the model.

Compared to schools where the majority of students are locals, girls do better than boys in schools with a mixed non-local and local population. In schools with 50-70% local students, girls score around 0.13-0.15 standard deviation higher than boys. Similarly, in schools where students are mostly from a rural background, girls consistently outperform boys in all subjects, with the biggest effect in Math and English. Remarkably, girls score 19.4% and 24.3% of a standard deviation higher than boys in Chinese and English in schools ranked medium and below in the local district. This difference amounts to one third of the female advantage in Chinese and English tests. These evidences corroborate previous findings that girls are generally less impacted by disruptive school environments compared to their male counterparts.

ROBUSTNESS CHECKS

This section performs two robustness checks. In the first one, I estimate the model separately for boys and girls, retaining the same explanatory variables as the main regression. The school-level covariates are excluded because of collinearity with the school-grade fixed effects. The model is of the following form

$$Y_{ijk} = \beta_0 + \mathbf{x}_{ijk} \beta_1 + D_{jk} + \epsilon_{ijk} \quad (2)$$

where $\mathbf{x}_{ijk}$ denotes the set of all individual, family, and teacher level covariates and $D_{jk}$ denotes the school-grade fixed effects. A selected set of results is presented in Table 4. The separate regressions comply with all the major findings in the main model. Being the only child is positively correlated with all test scores, but it benefits girls more on Math and boys more on Chinese and English. Rich kids do worse than the medium group, while rich
girls appear to score the lowest. Parental absence, especially that of mother, brings down all test scores for both genders. However, girls seem to suffer more from the absence of both parents, which squares with the observation that girls may have to take care of other siblings in the case where both parents are away from home. Noticeably, for the negative family composite variable, boys return large, negative, and significant estimates while those for girls are relatively smaller and mostly insignificant. This again substantiates the finding that girls do better than boys when residing in a difficult home environment.

For the teacher variable, boys benefit slightly more from having a female home teacher but are indifferent to the sex of the subject teacher. In contrast, girls have a substantial test score gain in Math and Chinese when the teachers are female.

The second robustness check simply tabulates the female-male test score gap in different subpopulations. Compared with the entire population, the female advantage in the group of the only child is larger in Math and smaller in the other two subjects. It further proves that being the only child helps each gender in the subjects that are stereotypically associated with the opposite sex. It is also conspicuous that students in lower-ranking schools, dysfunctional families, or poor households show larger gender gaps in all three subjects. The female advantage in English even reaches 77.1% of a standard deviation in lower-ranking schools. It is again the evidence that female advantages are more pronounced among disadvantaged students. In sum, the robustness checks are consistent with the findings of the main model.

DISCUSSION AND CONCLUSION

Using the recent data from China Education Panel Survey, this paper explores the “new gender gap” among Chinese middle school students. Girls in grade 7 and 9 outperform boys in Math, Chinese, and English, with gaps as large as more than 0.6 standard deviation. Consistent with past research with the same dataset, this paper finds that having a female Math and Chinese teacher disproportionally boosts girls’ test scores. Indeed, having a female Math teacher alone could explain nearly 70% of the reverse gender gap in Math in such classrooms.

Finally, it may be worthwhile to ask why a reverse gender gap in Math already emerged in China seven years ago, while in most of the developed countries with arguably higher degrees of gender equality, boys still outperform girls in Math today. One possible explanation might lie precisely in the fact that China is a developing country with a large urban/rural divide and uneven school qualities. As this paper demonstrates, girls are more resilient in disruptive school and family environments. Such resilience and adaptability might be why we have seen a striking “new gender gap” in the population.

This paper is certain to contain many inadequacies. While demonstrating strong correlational evidence between female advantage and family and school adversities, it is not possible to derive causal mechanisms of such an advantage. This paper also leaves many intriguing questions waiting to be explored: Does the impact of having a matched-sex teacher grow or diminish over time? Will the female advantage in Math be reversed in senior high school? Will the comparison across schools tell us more if a state standardized test is recorded? Findings in this paper might encourage future researchers to look into these questions in depth when more of the CEPS data becomes available.
### Table 1: Summary Statistics by Gender

<table>
<thead>
<tr>
<th></th>
<th>Full Sample</th>
<th>Male</th>
<th>Female</th>
<th>Mean Difference</th>
<th>Significant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Math score</td>
<td>69.988</td>
<td>69.348</td>
<td>70.699</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(9.960)</td>
<td>(10.281)</td>
<td>(9.542)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chinese score</td>
<td>69.907</td>
<td>66.968</td>
<td>73.176</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(9.974)</td>
<td>(10.432)</td>
<td>(8.294)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>English score</td>
<td>69.910</td>
<td>67.000</td>
<td>73.146</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(9.958)</td>
<td>(10.143)</td>
<td>(8.668)</td>
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</tr>
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</table>

**Student-level Variables**

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>0.473</td>
<td>0.000</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.499)</td>
<td>(0.000)</td>
<td>(0.000)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Being the only child</td>
<td>0.331</td>
<td>0.368</td>
<td>0.290</td>
<td>**</td>
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</tr>
<tr>
<td></td>
<td>(0.471)</td>
<td>(0.482)</td>
<td>(0.454)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Having rural Hukou</td>
<td>0.641</td>
<td>0.644</td>
<td>0.638</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.480)</td>
<td>(0.479)</td>
<td>(0.481)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Board in school</td>
<td>0.453</td>
<td>0.446</td>
<td>0.460</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.498)</td>
<td>(0.497)</td>
<td>(0.498)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Having disability/disorder</td>
<td>0.074</td>
<td>0.082</td>
<td>0.065</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.261)</td>
<td>(0.275)</td>
<td>(0.246)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cognitive test score</td>
<td>0.000</td>
<td>-0.013</td>
<td>0.015</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1.000)</td>
<td>(1.014)</td>
<td>(0.984)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Find grade6 Math Diff</td>
<td>0.395</td>
<td>0.331</td>
<td>0.468</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.489)</td>
<td>(0.470)</td>
<td>(0.499)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Find grade6 Chinese Diff</td>
<td>0.208</td>
<td>0.262</td>
<td>0.147</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.406)</td>
<td>(0.440)</td>
<td>(0.354)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Find grade6 English Diff</td>
<td>0.451</td>
<td>0.546</td>
<td>0.345</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.498)</td>
<td>(0.498)</td>
<td>(0.475)</td>
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</table>

**Family-level Variables**

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Family economic status:</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Poor</td>
<td>0.284</td>
<td>0.287</td>
<td>0.280</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.451)</td>
<td>(0.453)</td>
<td>(0.449)</td>
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<td></td>
</tr>
<tr>
<td>Medium</td>
<td>0.672</td>
<td>0.659</td>
<td>0.686</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.470)</td>
<td>(0.474)</td>
<td>(0.464)</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>Rich</td>
<td>0.041</td>
<td>0.049</td>
<td>0.033</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.199)</td>
<td>(0.215)</td>
<td>(0.178)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mother education:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elementary school and below</td>
<td>0.331</td>
<td>0.328</td>
<td>0.334</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.471)</td>
<td>(0.470)</td>
<td>(0.472)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Junior/Senior high school</td>
<td>0.588</td>
<td>0.592</td>
<td>0.584</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.492)</td>
<td>(0.491)</td>
<td>(0.493)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bachelor and above</td>
<td>0.079</td>
<td>0.077</td>
<td>0.080</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.269)</td>
<td>(0.267)</td>
<td>(0.272)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Father education:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elementary school and below</td>
<td>0.202</td>
<td>0.200</td>
<td>0.204</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.402)</td>
<td>(0.400)</td>
<td>(0.403)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Junior/Senior high school</td>
<td>0.698</td>
<td>0.704</td>
<td>0.691</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>(0.459)</td>
<td>(0.457)</td>
<td>(0.462)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bachelor and above</td>
<td>0.098</td>
<td>0.094</td>
<td>0.103</td>
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<tr>
<td></td>
<td>(0.297)</td>
<td>(0.291)</td>
<td>(0.304)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student migration status:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local student</td>
<td>0.895</td>
<td>0.888</td>
<td>0.903</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.306)</td>
<td>(0.315)</td>
<td>(0.295)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-local in-State students</td>
<td>0.063</td>
<td>0.069</td>
<td>0.056</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.243)</td>
<td>(0.254)</td>
<td>(0.229)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-local out-of-State students</td>
<td>0.038</td>
<td>0.038</td>
<td>0.039</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.192)</td>
<td>(0.190)</td>
<td>(0.194)</td>
<td></td>
<td></td>
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</tbody>
</table>

(Continued)
Table 1: Summary Statistics by Gender (Continued)

<table>
<thead>
<tr>
<th></th>
<th>Full Sample</th>
<th>Male</th>
<th>Female</th>
<th>Mean Difference Significant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parents absence:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Both parents at home</td>
<td>0.717</td>
<td>0.703</td>
<td>0.732</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.451)</td>
<td>(0.457)</td>
<td>(0.443)</td>
<td></td>
</tr>
<tr>
<td>Only mother is at home</td>
<td>0.107</td>
<td>0.112</td>
<td>0.102</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.309)</td>
<td>(0.315)</td>
<td>(0.302)</td>
<td>**</td>
</tr>
<tr>
<td>Only father is at home</td>
<td>0.038</td>
<td>0.046</td>
<td>0.028</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.190)</td>
<td>(0.210)</td>
<td>(0.164)</td>
<td></td>
</tr>
<tr>
<td>Neither is at home</td>
<td>0.139</td>
<td>0.139</td>
<td>0.139</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.346)</td>
<td>(0.346)</td>
<td>(0.346)</td>
<td></td>
</tr>
<tr>
<td>Negative family environment composite:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(= Father drunk + Parent fight + Parent in bad relation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.764</td>
<td>0.743</td>
<td>0.788</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.424)</td>
<td>(0.437)</td>
<td>(0.409)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.153</td>
<td>0.174</td>
<td>0.129</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.360)</td>
<td>(0.379)</td>
<td>(0.335)</td>
<td>**</td>
</tr>
<tr>
<td>2</td>
<td>0.067</td>
<td>0.066</td>
<td>0.068</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.250)</td>
<td>(0.248)</td>
<td>(0.252)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.016</td>
<td>0.018</td>
<td>0.015</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.127)</td>
<td>(0.132)</td>
<td>(0.121)</td>
<td></td>
</tr>
<tr>
<td>Teacher-level Variables</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Home teacher is female</td>
<td>0.558</td>
<td>0.546</td>
<td>0.571</td>
<td>**</td>
</tr>
<tr>
<td></td>
<td>(0.497)</td>
<td>(0.498)</td>
<td>(0.495)</td>
<td></td>
</tr>
<tr>
<td>Math teacher is female</td>
<td>0.501</td>
<td>0.501</td>
<td>0.502</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.500)</td>
<td>(0.500)</td>
<td>(0.500)</td>
<td></td>
</tr>
<tr>
<td>Chinese teacher is female</td>
<td>0.696</td>
<td>0.688</td>
<td>0.705</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.460)</td>
<td>(0.463)</td>
<td>(0.456)</td>
<td></td>
</tr>
<tr>
<td>English teacher is female</td>
<td>0.883</td>
<td>0.882</td>
<td>0.883</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.322)</td>
<td>(0.322)</td>
<td>(0.321)</td>
<td></td>
</tr>
<tr>
<td>Home teacher has bachelor degree</td>
<td>0.816</td>
<td>0.813</td>
<td>0.821</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.387)</td>
<td>(0.390)</td>
<td>(0.384)</td>
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</tr>
<tr>
<td>Math teacher has bachelor degree</td>
<td>0.797</td>
<td>0.804</td>
<td>0.790</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.402)</td>
<td>(0.397)</td>
<td>(0.407)</td>
<td></td>
</tr>
<tr>
<td>Chinese teacher has bachelor degree</td>
<td>0.820</td>
<td>0.809</td>
<td>0.832</td>
<td>**</td>
</tr>
<tr>
<td></td>
<td>(0.384)</td>
<td>(0.393)</td>
<td>(0.374)</td>
<td></td>
</tr>
<tr>
<td>English teacher has bachelor degree</td>
<td>0.800</td>
<td>0.799</td>
<td>0.802</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.400)</td>
<td>(0.401)</td>
<td>(0.399)</td>
<td></td>
</tr>
<tr>
<td>Home teacher experience:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Below 10 years</td>
<td>0.225</td>
<td>0.234</td>
<td>0.215</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.418)</td>
<td>(0.424)</td>
<td>(0.411)</td>
<td></td>
</tr>
<tr>
<td>10-20 years</td>
<td>0.501</td>
<td>0.499</td>
<td>0.504</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>(0.500)</td>
<td>(0.500)</td>
<td>(0.500)</td>
<td></td>
</tr>
<tr>
<td>More than 20 years</td>
<td>0.273</td>
<td>0.267</td>
<td>0.281</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.446)</td>
<td>(0.442)</td>
<td>(0.449)</td>
<td></td>
</tr>
<tr>
<td>Math teacher experience:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Below 10 years</td>
<td>0.205</td>
<td>0.210</td>
<td>0.198</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.403)</td>
<td>(0.407)</td>
<td>(0.399)</td>
<td></td>
</tr>
<tr>
<td>10-20 years</td>
<td>0.518</td>
<td>0.513</td>
<td>0.525</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.500)</td>
<td>(0.500)</td>
<td>(0.499)</td>
<td></td>
</tr>
<tr>
<td>More than 20 years</td>
<td>0.277</td>
<td>0.277</td>
<td>0.277</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.448)</td>
<td>(0.448)</td>
<td>(0.447)</td>
<td></td>
</tr>
<tr>
<td>Chinese teacher experience:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Below 10 years</td>
<td>0.278</td>
<td>0.287</td>
<td>0.268</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.448)</td>
<td>(0.453)</td>
<td>(0.443)</td>
<td></td>
</tr>
<tr>
<td>10-20 years</td>
<td>0.384</td>
<td>0.377</td>
<td>0.381</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.486)</td>
<td>(0.485)</td>
<td>(0.488)</td>
<td></td>
</tr>
<tr>
<td>More than 20 years</td>
<td>0.338</td>
<td>0.336</td>
<td>0.341</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.473)</td>
<td>(0.472)</td>
<td>(0.474)</td>
<td></td>
</tr>
</tbody>
</table>

(Continued)
Table 1: Summary Statistics by Gender (Continued)

<table>
<thead>
<tr>
<th></th>
<th>Full Sample</th>
<th>Male</th>
<th>Female</th>
<th>Mean Difference</th>
<th>Significant</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>English teacher experience:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Below 10 years</td>
<td>0.300</td>
<td>0.308</td>
<td>0.292</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.458)</td>
<td>(0.462)</td>
<td>(0.455)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-20 years</td>
<td>0.437</td>
<td>0.436</td>
<td>0.439</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.496)</td>
<td>(0.496)</td>
<td>(0.496)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>More than 20 years</td>
<td>0.263</td>
<td>0.257</td>
<td>0.269</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.440)</td>
<td>(0.437)</td>
<td>(0.444)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>School-level Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proportion of local students in school:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higher than 90% local students</td>
<td>0.695</td>
<td>0.687</td>
<td>0.703</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.461)</td>
<td>(0.464)</td>
<td>(0.457)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70-90% local students</td>
<td>0.210</td>
<td>0.214</td>
<td>0.205</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.407)</td>
<td>(0.410)</td>
<td>(0.404)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50-70% local students</td>
<td>0.057</td>
<td>0.059</td>
<td>0.054</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.231)</td>
<td>(0.236)</td>
<td>(0.226)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower than 50% local students</td>
<td>0.039</td>
<td>0.040</td>
<td>0.038</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.193)</td>
<td>(0.196)</td>
<td>(0.190)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proportion of students having rural hukou in school:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than 25% rural students</td>
<td>0.085</td>
<td>0.085</td>
<td>0.086</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.280)</td>
<td>(0.279)</td>
<td>(0.280)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25% to 60% rural students</td>
<td>0.282</td>
<td>0.273</td>
<td>0.292</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.450)</td>
<td>(0.445)</td>
<td>(0.455)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60% to 80% rural students</td>
<td>0.183</td>
<td>0.190</td>
<td>0.176</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.387)</td>
<td>(0.392)</td>
<td>(0.381)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>More than 80% rural students</td>
<td>0.449</td>
<td>0.452</td>
<td>0.446</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.497)</td>
<td>(0.498)</td>
<td>(0.497)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>School rank in local county/district:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Among the best</td>
<td>0.199</td>
<td>0.202</td>
<td>0.195</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.399)</td>
<td>(0.402)</td>
<td>(0.396)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Above average</td>
<td>0.639</td>
<td>0.626</td>
<td>0.653</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.480)</td>
<td>(0.484)</td>
<td>(0.476)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium and below</td>
<td>0.163</td>
<td>0.172</td>
<td>0.152</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.369)</td>
<td>(0.377)</td>
<td>(0.359)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>School type:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public school</td>
<td>0.917</td>
<td>0.901</td>
<td>0.935</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.275)</td>
<td>(0.298)</td>
<td>(0.247)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Private school</td>
<td>0.083</td>
<td>0.099</td>
<td>0.065</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.275)</td>
<td>(0.298)</td>
<td>(0.247)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>19028</td>
<td>9770</td>
<td>9258</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Weighted counts</strong></td>
<td>30743022</td>
<td>16208842</td>
<td>14534179</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: The entries are means and standard deviations for Grade 7 and Grade 9 students in the baseline survey whose Math, Chinese, and English scores are not all missing (the sample used in regression). Math, Chinese, and English test scores are the school-reported midterm scores for each student, standardized within each school-grade to have a mean of 70 and a standard deviation of 10. The cognitive test score is a test designed by CEPS to measure student’s cognitive abilities. Cognitive test score is normalized to have a mean of 0 and a SD of 1. Categorical variables are indicated by the subheadings which give the definition of the variables. The last column of the table displays the results of the test on the equality of means (t-test) for continuous and binary variables, and the test on the independence of distribution (Pearson chi-squared) for categorical variables. The sample weights are used, so the table could be interpreted as the inferential statistics for the Grade 7 and Grade 9 students in China. The last row displays the weighted counts for the full sample, boys, and girls in the population.

** Significant at the 1 percent level; * Significant at the 5 percent level
### Table 2: Boy-to-Girl Ratio in Test Score in Bottom and Top Percentiles

<table>
<thead>
<tr>
<th>Test Score Percentile</th>
<th>Mathematics</th>
<th>Chinese</th>
<th>English</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq 1^{st}$</td>
<td>1.66</td>
<td>6.35</td>
<td>5.69</td>
</tr>
<tr>
<td>$\leq 5^{th}$</td>
<td>1.69</td>
<td>4.77</td>
<td>4.75</td>
</tr>
<tr>
<td>$\leq 10^{th}$</td>
<td>1.52</td>
<td>3.91</td>
<td>3.78</td>
</tr>
<tr>
<td>$\geq 90^{th}$</td>
<td>1.03</td>
<td>0.37</td>
<td>0.44</td>
</tr>
<tr>
<td>$\geq 95^{th}$</td>
<td>1.05</td>
<td>0.32</td>
<td>0.43</td>
</tr>
<tr>
<td>$\geq 99^{th}$</td>
<td>1.19</td>
<td>0.34</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Boy-to-girl ratio in the population: 1.12

Notes: This table displays the boy-to-girl ratio in different percentiles of the test score distribution. $\leq 1^{st}$ includes the 0th percentile and the 1st percentile, etc. Sample weights are used. The last row denotes the boys-to-girls ratio in the underlying population.

### Table 3: Main Regression

<table>
<thead>
<tr>
<th></th>
<th>(1) Mathematics</th>
<th>(2) Chinese</th>
<th>(3) English</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mathematics</td>
<td>Chinese</td>
<td>English</td>
</tr>
<tr>
<td>Panel A: Student-level Variables</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>-2.647**</td>
<td>4.951***</td>
<td>2.681**</td>
</tr>
<tr>
<td></td>
<td>(1.699)</td>
<td>(1.330)</td>
<td>(1.419)</td>
</tr>
<tr>
<td>Being the only child</td>
<td>0.454−</td>
<td>0.718*</td>
<td>1.012***</td>
</tr>
<tr>
<td></td>
<td>(0.278)</td>
<td>(0.298)</td>
<td>(0.298)</td>
</tr>
<tr>
<td>Female × Being the only child</td>
<td>0.200</td>
<td>-0.533−</td>
<td>-0.645+</td>
</tr>
<tr>
<td></td>
<td>(0.376)</td>
<td>(0.371)</td>
<td>(0.359)</td>
</tr>
<tr>
<td>Rural Hukou</td>
<td>0.726**</td>
<td>0.308−</td>
<td>0.0883</td>
</tr>
<tr>
<td></td>
<td>(0.236)</td>
<td>(0.235)</td>
<td>(0.231)</td>
</tr>
<tr>
<td>Board in school</td>
<td>0.643+</td>
<td>0.604+</td>
<td>0.542+</td>
</tr>
<tr>
<td></td>
<td>(0.354)</td>
<td>(0.342)</td>
<td>(0.319)</td>
</tr>
<tr>
<td>Having disability/disorder</td>
<td>-1.240***</td>
<td>-1.816***</td>
<td>-0.829**</td>
</tr>
<tr>
<td></td>
<td>(0.341)</td>
<td>(0.371)</td>
<td>(0.314)</td>
</tr>
<tr>
<td>Cognitive test score</td>
<td>4.286***</td>
<td>3.678***</td>
<td>3.723***</td>
</tr>
<tr>
<td></td>
<td>(0.146)</td>
<td>(0.122)</td>
<td>(0.127)</td>
</tr>
<tr>
<td>Find grade6 Math/Chinese/English hard</td>
<td>-4.875***</td>
<td>-2.706***</td>
<td>-4.845***</td>
</tr>
<tr>
<td></td>
<td>(0.239)</td>
<td>(0.222)</td>
<td>(0.233)</td>
</tr>
<tr>
<td>School-grade Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Number of Observations</td>
<td>18990</td>
<td>19001</td>
<td>18996</td>
</tr>
</tbody>
</table>

Notes: This table displays point estimates and standard errors of the estimate in the parenthesis. The sample included is for students who do not have missing values for the respective test scores. The dummy variables that flag each missing variable are omitted. The standard errors are clustered at the school-grade level. Sample weights are used. Panel A, B, C, D display the subsets of results from the same regression.

Significance levels: $−p < 0.20$, $+p < 0.10$, $*p < 0.05$, $**p < 0.01$, $***p < 0.001$
### Table 3: Main Regression

<table>
<thead>
<tr>
<th></th>
<th>(1) Mathematics</th>
<th>(2) Chinese</th>
<th>(3) English</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Family economic status:</strong> (base group: Medium)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poor</td>
<td>-0.166</td>
<td>0.0370</td>
<td>-0.158</td>
</tr>
<tr>
<td></td>
<td>(0.199)</td>
<td>(0.215)</td>
<td>(0.198)</td>
</tr>
<tr>
<td>Rich</td>
<td>-0.828*</td>
<td>-0.517*</td>
<td>-0.727*</td>
</tr>
<tr>
<td></td>
<td>(0.387)</td>
<td>(0.355)</td>
<td>(0.368)</td>
</tr>
<tr>
<td><strong>Mother education:</strong> (base group: Elementary school and below)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Junior/Senior high school</td>
<td>0.290−</td>
<td>0.166</td>
<td>0.0688</td>
</tr>
<tr>
<td></td>
<td>(0.217)</td>
<td>(0.231)</td>
<td>(0.196)</td>
</tr>
<tr>
<td>Bachelor and above</td>
<td>1.757***</td>
<td>1.623***</td>
<td>1.503***</td>
</tr>
<tr>
<td></td>
<td>(0.400)</td>
<td>(0.446)</td>
<td>(0.375)</td>
</tr>
<tr>
<td><strong>Father education:</strong> (base group: Elementary school and below)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Junior/Senior high school</td>
<td>0.315−</td>
<td>0.598*</td>
<td>0.708**</td>
</tr>
<tr>
<td></td>
<td>(0.222)</td>
<td>(0.243)</td>
<td>(0.222)</td>
</tr>
<tr>
<td>Bachelor and above</td>
<td>1.431***</td>
<td>1.816***</td>
<td>1.836***</td>
</tr>
<tr>
<td></td>
<td>(0.382)</td>
<td>(0.436)</td>
<td>(0.376)</td>
</tr>
<tr>
<td><strong>Parental absence</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Only mother is at home</td>
<td>-0.153</td>
<td>-0.0386</td>
<td>-0.128</td>
</tr>
<tr>
<td></td>
<td>(0.292)</td>
<td>(0.279)</td>
<td>(0.221)</td>
</tr>
<tr>
<td>Only father is at home</td>
<td>-1.131*</td>
<td>-0.681−</td>
<td>-0.999*</td>
</tr>
<tr>
<td></td>
<td>(0.459)</td>
<td>(0.482)</td>
<td>(0.438)</td>
</tr>
<tr>
<td>Neither is at home</td>
<td>-0.421−</td>
<td>-0.286</td>
<td>-0.259</td>
</tr>
<tr>
<td></td>
<td>(0.302)</td>
<td>(0.294)</td>
<td>(0.280)</td>
</tr>
<tr>
<td><strong>Negative family environment composite:</strong> (base group: 0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-0.449−</td>
<td>-0.836*</td>
<td>-0.525+</td>
</tr>
<tr>
<td></td>
<td>(0.301)</td>
<td>(0.330)</td>
<td>(0.277)</td>
</tr>
<tr>
<td>2</td>
<td>-0.924*</td>
<td>-0.641</td>
<td>-1.133*</td>
</tr>
<tr>
<td></td>
<td>(0.401)</td>
<td>(0.504)</td>
<td>(0.515)</td>
</tr>
<tr>
<td>3</td>
<td>-1.633−</td>
<td>-1.826+</td>
<td>-0.946</td>
</tr>
<tr>
<td></td>
<td>(1.005)</td>
<td>(1.051)</td>
<td>(1.008)</td>
</tr>
<tr>
<td>Female × 1</td>
<td>0.526</td>
<td>0.620−</td>
<td>0.156</td>
</tr>
<tr>
<td></td>
<td>(0.436)</td>
<td>(0.415)</td>
<td>(0.496)</td>
</tr>
<tr>
<td>Female × 2</td>
<td>0.295</td>
<td>-0.319</td>
<td>0.384</td>
</tr>
<tr>
<td></td>
<td>(0.585)</td>
<td>(0.607)</td>
<td>(0.646)</td>
</tr>
<tr>
<td>Female × 3</td>
<td>2.611*</td>
<td>1.545</td>
<td>1.474</td>
</tr>
<tr>
<td></td>
<td>(1.303)</td>
<td>(1.338)</td>
<td>(1.408)</td>
</tr>
</tbody>
</table>

**Notes:** This panel presents the result for family-level variables. The negative family composite score is defined as the sum of "Father drunk", "Parent fight", and "Parent in bad relation" dummies. For example, if a student reports all three of the situations above, the student has a composite score of 3. Student migration status (3 categories) is included in the regression but not displayed here due to space. Significance levels: − p < 0.20, + p < 0.10, * p < 0.05, ** p < 0.01, *** p < 0.001
Table 3: Main Regression
Dependent Variable: Standardized Mathematics/Chinese/English scores (Mean=70, SD=10)

<table>
<thead>
<tr>
<th>Panel C: Teacher-level Variables</th>
<th>Mathematics</th>
<th>Chinese</th>
<th>English</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home teacher is female</td>
<td>0.863**</td>
<td>2.009**</td>
<td>1.654**</td>
</tr>
<tr>
<td>(0.609)</td>
<td>(0.660)</td>
<td>(0.571)</td>
<td></td>
</tr>
<tr>
<td>Subject teacher is female</td>
<td>0.311</td>
<td>-0.0409</td>
<td>-0.248</td>
</tr>
<tr>
<td>(0.828)</td>
<td>(0.948)</td>
<td>(0.955)</td>
<td></td>
</tr>
<tr>
<td>Female × Home teacher is female</td>
<td>-0.268</td>
<td>-0.970*</td>
<td>-0.297</td>
</tr>
<tr>
<td>(0.471)</td>
<td>(0.450)</td>
<td>(0.396)</td>
<td></td>
</tr>
<tr>
<td>Female × Subject teacher is female</td>
<td>0.947*</td>
<td>1.146*</td>
<td>0.0458</td>
</tr>
<tr>
<td>(0.460)</td>
<td>(0.508)</td>
<td>(0.599)</td>
<td></td>
</tr>
</tbody>
</table>

| School-grade Fixed Effects       | Yes         | Yes     | Yes     |
| Number of Observations           | 18990       | 19001   | 18996   |

Notes: This panel presents the result for teacher-level variables. The variables in the regression but not displayed here are: whether the home teacher has a bachelor degree, whether the subject teacher has a bachelor degree, teaching experience of home teacher (3 categories), teaching experience of subject teacher (3 categories).
Significance levels: * p < 0.20, + p < 0.10, * p < 0.05, ** p < 0.01, *** p < 0.001

Table 3: Main Regression
Dependent Variable: Standardized Mathematics/Chinese/English scores (Mean=70, SD=10)

<table>
<thead>
<tr>
<th>Panel D: School-level Variables</th>
<th>Mathematics</th>
<th>Chinese</th>
<th>English</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion of local students in the school: (base group: More than 90%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female × 70-90% local students</td>
<td>1.409*</td>
<td>-0.131</td>
<td>0.118</td>
</tr>
<tr>
<td>(0.543)</td>
<td>(0.560)</td>
<td>(0.448)</td>
<td></td>
</tr>
<tr>
<td>Female × 50-70% local students</td>
<td>1.555*</td>
<td>1.280*</td>
<td>1.349+</td>
</tr>
<tr>
<td>(0.905)</td>
<td>(0.849)</td>
<td>(0.709)</td>
<td></td>
</tr>
<tr>
<td>Female × lower than 50% local students</td>
<td>1.237</td>
<td>-0.167</td>
<td>-0.186</td>
</tr>
<tr>
<td>(1.493)</td>
<td>(0.825)</td>
<td>(0.955)</td>
<td></td>
</tr>
<tr>
<td>Proportion of students with rural Hukou (base group: Less than 25%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female × 25-60% rural students</td>
<td>0.726</td>
<td>0.768−</td>
<td>0.805+</td>
</tr>
<tr>
<td>(0.679)</td>
<td>(0.526)</td>
<td>(0.469)</td>
<td></td>
</tr>
<tr>
<td>Female × 60-80% rural students</td>
<td>0.962</td>
<td>0.474</td>
<td>0.902−</td>
</tr>
<tr>
<td>(0.830)</td>
<td>(0.773)</td>
<td>(0.659)</td>
<td></td>
</tr>
<tr>
<td>Female × more than 80% rural students</td>
<td>1.777*</td>
<td>0.400</td>
<td>1.308*</td>
</tr>
<tr>
<td>(0.803)</td>
<td>(0.753)</td>
<td>(0.649)</td>
<td></td>
</tr>
<tr>
<td>School rank in local county/district: (base group: Among the best)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female × Medium and above</td>
<td>0.787−</td>
<td>0.867−</td>
<td>1.153*</td>
</tr>
<tr>
<td>(0.594)</td>
<td>(0.560)</td>
<td>(0.529)</td>
<td></td>
</tr>
<tr>
<td>Female × Medium and below</td>
<td>0.982</td>
<td>1.940**</td>
<td>2.428***</td>
</tr>
<tr>
<td>(0.867)</td>
<td>(0.717)</td>
<td>(0.674)</td>
<td></td>
</tr>
<tr>
<td>Female × Public school</td>
<td>1.848</td>
<td>-0.816</td>
<td>0.513</td>
</tr>
<tr>
<td>(1.338)</td>
<td>(1.203)</td>
<td>(1.127)</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>72.77***</td>
<td>65.86***</td>
<td>70.58***</td>
</tr>
<tr>
<td>(1.54)</td>
<td>(1.82)</td>
<td>(1.95)</td>
<td></td>
</tr>
</tbody>
</table>

| School-grade Fixed Effects       | Yes         | Yes     | Yes     |
| Number of Observations           | 18990       | 19001   | 18996   |

Notes: This panel presents the result for school-level variables. The point estimates for these variables are omitted because of collinearity with school-fixed effects.
Significance levels: * p < 0.20, + p < 0.10, * p < 0.05, ** p < 0.01, *** p < 0.001
### Table 4: Separate Regression For Boys and Girls

<table>
<thead>
<tr>
<th></th>
<th>Boys</th>
<th>Girls</th>
<th>Boys</th>
<th>Girls</th>
<th>Boys</th>
<th>Girls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Math</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Being the only child</td>
<td>0.445*</td>
<td>0.619*</td>
<td>0.780*</td>
<td>0.257</td>
<td>0.842**</td>
<td>0.698*</td>
</tr>
<tr>
<td>Family economic status:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poor</td>
<td>-0.411*</td>
<td>0.266</td>
<td>-0.397*</td>
<td>0.474*</td>
<td>-0.520*</td>
<td>0.262</td>
</tr>
<tr>
<td>Rich</td>
<td>-0.542*</td>
<td>-1.436*</td>
<td>-0.302</td>
<td>-0.949*</td>
<td>-0.517</td>
<td>-1.163*</td>
</tr>
<tr>
<td>Parent at home variables:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Only mother at home</td>
<td>-0.144</td>
<td>-0.113</td>
<td>0.259</td>
<td>-0.311</td>
<td>0.00423</td>
<td>-0.203</td>
</tr>
<tr>
<td>Only father at home</td>
<td>-1.123*</td>
<td>-1.377*</td>
<td>-0.730</td>
<td>-0.463</td>
<td>-1.075*</td>
<td>-0.878</td>
</tr>
<tr>
<td>Neither at home</td>
<td>-0.220</td>
<td>-0.720*</td>
<td>0.122</td>
<td>-0.674*</td>
<td>-0.0629</td>
<td>-0.432</td>
</tr>
<tr>
<td>Negative family environment composite:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-0.440*</td>
<td>0.0532</td>
<td>-0.844*</td>
<td>-0.231</td>
<td>-0.575*</td>
<td>-0.386</td>
</tr>
<tr>
<td>2</td>
<td>-0.961*</td>
<td>-0.691*</td>
<td>-0.623</td>
<td>-1.041*</td>
<td>-1.048*</td>
<td>-0.826*</td>
</tr>
<tr>
<td>3</td>
<td>-1.537</td>
<td>0.906</td>
<td>-1.835*</td>
<td>-0.314</td>
<td>-0.994</td>
<td>0.492</td>
</tr>
<tr>
<td>Female home teacher</td>
<td>1.197*</td>
<td>0.0778</td>
<td>1.780*</td>
<td>1.327*</td>
<td>1.527*</td>
<td>1.439*</td>
</tr>
<tr>
<td>Female subject teacher</td>
<td>0.243</td>
<td>1.505*</td>
<td>-0.495</td>
<td>1.517*</td>
<td>-0.421</td>
<td>0.0675</td>
</tr>
<tr>
<td>School-grade FE</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Number of Observations</td>
<td>9741</td>
<td>9249</td>
<td>9748</td>
<td>9253</td>
<td>9748</td>
<td>9248</td>
</tr>
</tbody>
</table>

**Notes:** This table displays separate regressions on the subsample of boys and girls. All the explanatory variables, except for the school-level variables, are kept from the main regression, but only a selected set of the results are displayed. All specifications include school-grade fixed effects. The standard errors are clustered at the school-grade level. Sample weights are used.

### Table 5: The Female-male Test Score Gap in Subpopulations

<table>
<thead>
<tr>
<th></th>
<th>Math</th>
<th>Chinese</th>
<th>English</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>1.35</td>
<td>6.21</td>
<td>6.15</td>
</tr>
<tr>
<td>The only child</td>
<td>1.77</td>
<td>6.02</td>
<td>5.66</td>
</tr>
<tr>
<td>Students in lower-ranking schools</td>
<td>1.87</td>
<td>7.10</td>
<td>7.71</td>
</tr>
<tr>
<td>Students in dysfunctional families</td>
<td>1.72</td>
<td>6.73</td>
<td>6.58</td>
</tr>
<tr>
<td>Students in poor households</td>
<td>1.46</td>
<td>6.84</td>
<td>7.01</td>
</tr>
</tbody>
</table>

**Notes:** This table displays the female-male test score gap in different subpopulations. Lower-ranking schools refer to schools that are ranked at medium and below in the local county or district. Students in dysfunctional family refer to students whose negative family composite score is greater than or equal to 1. Students in poor households are students whose family economic status is "poor". Sample weights are used.
REFERENCES


ACKNOWLEDGMENTS

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The Impact of Hospital Concentration on Municipal Finances

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1Department of Economics, Yale University

ABSTRACT

Since adoption of the Affordable Care Act, hospital concentration has increased across the country, with alarming implications for healthcare affordability. This paper finds evidence that hospital concentration is associated with increases in tax revenue and property tax revenue per capita within a city. The relationship between hospital concentration and taxes is strongest in cities with higher tax revenues, with higher nonprofit ownership shares, and that financially support their hospitals. This paper investigates two potential mechanisms through which hospital concentration may increase tax revenues within a city—specifically, the effect of concentration on changes in nonprofit or for-profit hospital ownership and the effect of concentration on capital investments—failing to find strong supporting evidence for either. Beyond hospital concentration's role in healthcare price growth across the country, this paper may provide a starting point for further investigation into the impact of hospital mergers and concentration on city governments and other actors.

INTRODUCTION

Hospitals, according to Gaynor, Ho, and Town (2015), make up 5.6% of U.S. GDP. Since the passage of the Affordable Care Act, Schmitt (2017) reports, “there has been a sharp uptick in hospital mergers, with the number of deals essentially doubling within three years.” According to Cooper, Craig, Gaynor, and van Reenen (2019), merging hospitals are mostly large, well-respected nonprofits and “tend to be located in less concentrated markets” where they are less likely to draw antitrust scrutiny. Increased concentration likely strengthens hospitals’ negotiating power with insurers, resulting in higher rates.

The impact of hospital concentration on municipal finances is not well understood. Given that hospital concentration increases prices for patients and hospitals receive substantial tax incentives, the question of whether hospitals earn their government assistance is a pressing one. When tax revenues decrease, cities must cut public services, including education, food assistance, and public safety. With Jonas (2012) calculating that city property tax revenues fell by 3.2% on average and by up to 25% during the Great Recession and with cities taking a financial hit from coronavirus-related shutdowns, understanding the role of one of the largest industries in the country and in many cities, hospitals, on municipal finances is important.

If hospital concentration contributes to this trend, policymakers need to know.

In this paper, I use a city fixed effects model to study the relationship between hospital concentration and taxes. I identify this model based on changes in hospital concentration within a city over time, as opposed to differences across cities. Utilizing panel data on hospital size from 2001 to 2014, I construct a measure of hospital concentration and system concentration within each city. With the Lincoln Institute’s fiscally standardized dataset on municipal finances, I measure the effect of changes in hospital concentration on tax revenue within a city. I then split cities above and below median tax revenues and median for-profit and nonprofit hospital ownership shares to gauge which types of cities are powering the relationship between hospital concentration and taxes. Finally, utilizing a RAND dataset containing hospital ownership shares and capital expenditures across markets, I explore two mechanisms through which hospital concentration could affect municipal finances: changes in ownership status after mergers and capital construction.

I find evidence that growth in hospital concentration as measured by the Herfindahl-Hirschmann Index (HHI) within a city increases municipal taxes and property taxes per capita. A 10% increase in hospital concentration is
associated with a moderately significant increase in taxes per capita of 1.6% within a city. Though statistically insignificant, a 10% increase in HHI corresponds to an approximately 2% increase in property tax revenue per capita within a city. That the property tax result is larger than that for all tax revenues combined suggests that changes in property taxes may be driving the relationship between hospital concentration and taxes. System concentration also appears to increase municipal finances. My heterogeneity analysis reveals that the relationship between hospital concentration and municipal finances is largest in cities with high taxes and high nonprofit ownership shares.

Turning to mechanisms, my analyses fail to support the hypothesis that changes in the for-profit or nonprofit hospital share are responsible for the positive relationship between HHI and tax revenue per capita within a city. Instead, I find that only growth in the government-run hospital share increases tax revenue, which may be a case of reverse causality. Because cities can tax for-profit hospitals, I anticipated a positive relationship between the for-profit ownership share and property taxes per capita. Surprisingly, I find that a 10% increase in the share of for-profit hospitals corresponds to a 2.3% decrease in property tax revenue, whereas the share of nonprofit hospitals had next to no effect on property taxes. Next, I analyze whether hospital construction and expansion explain changes in capital construction and, through construction, the increase in taxes per capita within cities. While my results show that increases in HHI statistically significantly reduce various measures of capital construction within cities, I identify no relationship between capital expenditures and tax revenue.

My paper contributes to the literature by establishing a relationship, whether causal or not, between hospital concentration and city tax revenue. By investigating the repercussions of hospital concentration on city governments as opposed to healthcare prices, costs, and outcomes, I am contributing novel research to the existing literature and providing a starting point for future investigation.

One limitation of my research is that because including fixed effects limits my analysis to variation within cities, the city fixed effects cannot account for time-varying characteristics within cities. For example, my city fixed effects model would not control for a shock, such as Hurricane Katrina, that affects one city’s taxes and economic growth and not others. Similarly, city fixed effects cannot account for differences in regional economic development. Without supporting evidence for a causal pathway through which hospital concentration might increase tax revenue, I cannot verify causation. Another limitation of my study is that the RAND dataset on hospital capital and ownership status does not encompass all the cities in the Lincoln Institute data and the city definitions differ slightly, making comparisons across the two datasets imperfect.

**LITERATURE REVIEW**

Research shows that hospital consolidation raises prices on consumers. Applying difference-in-differences to health insurance claims data, Cooper et al. (2019) discovered that “prices increased by over 6% when the merging hospitals were geographically close (e.g., 5 miles or less apart), but not when the hospitals were geographically distant (e.g., over 25 miles apart).” Alarmingly, Dafny (2009) found that non-merging hospitals respond to the merger of their rivals by increasing their own prices by up to 40%. Comparing insurer and hospital concentration, Melnick, Shen, and Wu (2011) determined that hospital concentration raises prices for consumers while insurer concentration lowers prices. Unfortunately for consumers, 90% of hospitals operate in markets wherein hospital concentration exceeds insurance plan concentration. Hospitals get away with price increases because consumers “choose hospitals largely ignoring the hospital’s price,” according to Garmon (2013).

Hospitals, especially nonprofit ones, receive substantial government support. By exempting nonprofit hospitals from “federal income tax, state income tax, state and local sales taxes, and local property tax,” nonprofit hospitals received a subsidy of $24.6 billion in 2011, Rosenbaum et al. (2015) estimated. In response to calls to increase their community benefit spending, nonprofit hospitals, which make up 47% of all US hospitals, according to the American Hospital Association, raised their community benefit spending from 7.6% of operating expenses in 2010 to 8.1% in 2014, Young et al. (2018) calculated. Herring et al. (2018) found that “incremental community benefit spending”—how much more nonprofit hospitals spend on charity care and community benefit programs than for-profit hospitals—exceeded the tax exemption for only 62% of nonprofit hospitals.

As nonprofit hospitals consolidate and raise prices, they continue to receive substantial tax breaks. With many municipalities in financial trouble thanks to coronavirus and critics questioning hospitals’ community benefit spending, understanding the effect of hospital concentration on municipal finances is an important policy concern.
DATA DESCRIPTION

1. Hospital Merger Data

Cooper et al.’s “The Price Ain’t Right” (2019) contains a hospital merger dataset with the ownership status of 2,358 out of 3,272 hospitals in the American Hospital Association (AHA) from 2001 to 2014. These publicly-available data include system affiliation, latitude and longitude, and hospital bed count. The authors’ unique location and system identifiers made possible the calculation of market concentration using HHI.

2. Lincoln Institute Data

Founded in 1946, the Lincoln Institute of Land Policy maintains a dataset, “Fiscally Standardized Cities,” on the finances of 150 American cities from 1977 to 2016, including tax revenues and expenditures. I have limited my analysis to the 147 cities with at least one hospital in the Cooper et al. (2019) dataset and the period 2001-2014 to match Cooper et al.’s (2019).

For the purposes of this paper, I use only 20 measures encompassing taxes, revenues, and spending. All values are per capita, enabling straightforward comparisons across cities. Because some city jurisdictions may overlap with county governments, the Lincoln Institute created fiscally standardized (FiSC) indicators by “adding together revenues and expenditures for the city government plus an appropriate share from overlying counties, school districts, and special districts…based on a city’s share of county population, the percentage of students in each school district that live in the central city, and the city’s share of the estimated population served by each special district,” according to Langley (2016). I will be restricting my analysis to FiSC variables to sidestep complications with overlapping government jurisdictions. This is a widely-accepted practice for research across cities with variable governmental structures. The IMF’s Jiri Jonas (2012) used a similar “constructed cities” method to estimate the costs of the Great Recession on local governments and other researchers, including Chernick and Reschovsky (2017), have used the Lincoln Institute’s dataset for papers in the Journal of Urban Affairs, for the Pew Charitable Trust, and for the Federal Reserve.

3. RAND Market-Level Hospital Data

Using CMS Medicare cost reports, the RAND Corporation compiled metrics on hospital profits, costs, ownership status, and more. RAND aggregates the data at hospital, county, market, and state levels. To facilitate comparisons across Lincoln Institute and RAND measures, I have opted for market-level indicators. 115 markets in the RAND dataset match, imperfectly, cities in the Lincoln data. Unlike the Lincoln Institute data, RAND market indicators may not be confined to city limits. However, as an approximation, RAND markets and Lincoln cities are useful. Because the Lincoln Institute compiles its data on a per-capita basis, I calculated population-weighted averages for Lincoln Institute cities to create matching, aggregated “markets” in cases where RAND lists several cities under one market name, such as “Los Angeles-Long Beach-Anaheim, CA.”

RESEARCH DESIGN

1. Creating Measures of HHI and System HHI

HHI is a measure of market concentration used in the academic literature and by the Department of Justice (DOJ) in antitrust cases. The DOJ considers markets with HHI scores between 0 and 1,500 un-concentrated, between 1,500 and 2,500 moderately concentrated, and between 2,500 and 10,000 highly concentrated. This paper uses hospital beds, as compiled in Cooper et al. (2019), as a proxy for market share. For a given market with $n$ hospitals, its HHI is the sum of each hospital’s share, $s_i$, squared:

$$HHI = s_1^2 + s_2^2 + \cdots + s_{n-1}^2 + s_n^2 = \sum_{i=1}^{n} s_i^2,$$

where

$$s_i = \frac{\text{Hospital Bed Count}_i}{\sum_{i=1}^{n} \text{Hospital Bed Count}_i} \times 100$$

Any measure of hospital concentration that ignores hospital systems is likely to understate market concentration. Thus, within each city, I grouped hospitals by system to calculate system market share. For a market with $N$ systems,

$$S_i = \frac{\text{Hospital System Bed Count}_i}{\sum_{i=1}^{N} \text{Hospital System Bed Count}_i} \times 100$$

Using hospital system market share, I calculated system HHI:

$$\text{System HHI} = S_1^2 + S_2^2 + \cdots + S_{n-1}^2 + S_n^2 = \sum_{i=1}^{n} S_i^2$$

2. City Fixed Effects Model

To estimate the effect of hospital concentration on taxes and property taxes per capita, I employed a city fixed ef-
Effects model with standard errors clustered by city and year controls. Fixed effects isolate the impact of a change in one indicator on another within a city over time, holding all other time-invariant, city characteristics equal:

$$
\tilde{Y}_i = \beta_1 \cdot \tilde{X}_i + \text{City Effects} + \text{Time Fixed Effects} + \tilde{u}_i
$$

The coefficient of interest, $\beta_1$, captures the effect of the independent variable $X$—the logarithm of HHI, system HHI, or another variable—on the dependent variable $Y$—the logarithm of a measure of municipal finances such as tax revenue per capita. I scaled my estimates such that the coefficient represents the effect of an approximately 10% change in HHI. Year fixed effects control for trends across time, such as overall changes in tax revenues across time resulting from macroeconomic events unrelated to hospital concentration. All standard errors are clustered at the city level to account for serial correlation in the estimates of a city over time. Results are weighted by city population because city populations vary from a low of 16,000 to more than 8,000,000 and small cities tend to have highly concentrated hospital sectors, distorting the results in one direction.

A city fixed effects model does not inherently demonstrate causality but is usually more accurate than simple regressions across cities because it discards cross-city variation in financial structure. Small cities tend to have more concentrated hospital sectors than large cities and tax residents less. Taking an ordinary least squares (OLS) regression across small and large cities, therefore, is likely to find that taxes and hospital sectors are negatively correlated. A city fixed effects regression, by contrast, isolates the impact of hospital concentration on taxes within a city over time.

RESULTS

1. Summary Statistics

Table 1 reports my summary statistics.

Most cities have highly concentrated hospital sectors, with a mean HHI and mean system HHI of 4,661 and 5,306, respectively—well above the DOJ threshold of 2,500. Because systems own multiple hospitals, system HHI logically exceeds HHI.

2. Hospital Concentration and Taxes

Table 2 displays my primary estimates of the relationship between HHI and taxes.

The estimates in column 1 come from an OLS regression between HHI and taxes per capita across cities. Column 2 adds the results of a fixed effects regression between HHI and tax revenues per capita. Column 3 displays the estimates of the OLS regression between system HHI and taxes. Column 4 exhibits the fixed effects results of system HHI and taxes. Columns 5 through 8 do the same for HHI and property taxes per capita.

Although the OLS regression across cities suggests a negative relationship between hospital concentration (HHI) and taxes per capita, the fixed effects model, which examines variation within a city and accounts for time effects, shows a positive and moderately significant relationship between HHI and taxes per capita: a 10% increase in HHI is associated with an approximately 1.6% increase in taxes per capita. Whereas the OLS regression captures that small cities tend to have concentrated hospital sectors and low rates of taxation, fixed effects indicate that an increase

<table>
<thead>
<tr>
<th>Statistic</th>
<th>N</th>
<th>Mean</th>
<th>St. Dev.</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>HHI</td>
<td>2,058</td>
<td>4,660.8</td>
<td>2,771.1</td>
<td>291.3</td>
<td>10,000.0</td>
</tr>
<tr>
<td>System HHI</td>
<td>2,058</td>
<td>5,306.2</td>
<td>2,602.1</td>
<td>666.7</td>
<td>10,000.0</td>
</tr>
<tr>
<td>Taxes per capita</td>
<td>2,058</td>
<td>1,977.6</td>
<td>878.1</td>
<td>692.9</td>
<td>10,539.9</td>
</tr>
<tr>
<td>Property Taxes per capita</td>
<td>2,058</td>
<td>1,276.6</td>
<td>485.3</td>
<td>260.2</td>
<td>3,455.2</td>
</tr>
<tr>
<td>City Population</td>
<td>2,058</td>
<td>432,957.9</td>
<td>788,949.4</td>
<td>16,004</td>
<td>8,000,000</td>
</tr>
<tr>
<td>CPI</td>
<td>2,058</td>
<td>1.2</td>
<td>0.1</td>
<td>0</td>
<td>1.4</td>
</tr>
<tr>
<td>Total Revenue per capita</td>
<td>2,058</td>
<td>6,050.4</td>
<td>2,176.8</td>
<td>2,293.3</td>
<td>20,935.9</td>
</tr>
<tr>
<td>General Revenue per capita</td>
<td>2,058</td>
<td>5,283.0</td>
<td>1,843.3</td>
<td>2,083.8</td>
<td>19,520.8</td>
</tr>
<tr>
<td>General Sales Tax per capita</td>
<td>2,058</td>
<td>279.1</td>
<td>289.6</td>
<td>0</td>
<td>1,872.9</td>
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<tr>
<td>Gross Revenues Sales Tax per capita</td>
<td>2,058</td>
<td>420.2</td>
<td>352.2</td>
<td>0</td>
<td>2,697.7</td>
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<tr>
<td>Direct Spending per capita</td>
<td>2,058</td>
<td>6,149.7</td>
<td>2,171.1</td>
<td>2,301.3</td>
<td>21,923.7</td>
</tr>
<tr>
<td>General Spending per capita</td>
<td>2,058</td>
<td>5,224.6</td>
<td>1,808.9</td>
<td>1,978.4</td>
<td>20,999.4</td>
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<td>Education Spending per capita</td>
<td>2,058</td>
<td>1,780.5</td>
<td>553.3</td>
<td>0</td>
<td>4,711.2</td>
</tr>
<tr>
<td>Health Spending per capita</td>
<td>2,058</td>
<td>152.7</td>
<td>167.9</td>
<td>0</td>
<td>1,214.0</td>
</tr>
<tr>
<td>Social Services Spending per capita</td>
<td>2,058</td>
<td>583.8</td>
<td>181.6</td>
<td>0</td>
<td>6,278.2</td>
</tr>
<tr>
<td>Public Welfare Spending per capita</td>
<td>2,058</td>
<td>181.9</td>
<td>396.1</td>
<td>0</td>
<td>5,174.0</td>
</tr>
<tr>
<td>Hospital Spending per capita</td>
<td>2,058</td>
<td>249.2</td>
<td>607.3</td>
<td>0</td>
<td>5,564.4</td>
</tr>
<tr>
<td>Corporate Income Tax Revenue per capita</td>
<td>2,058</td>
<td>3.4</td>
<td>81.9</td>
<td>0</td>
<td>1,013</td>
</tr>
<tr>
<td>Individual Income Tax Revenue per capita</td>
<td>2,058</td>
<td>109.3</td>
<td>310.5</td>
<td>0</td>
<td>2,663.4</td>
</tr>
</tbody>
</table>

Notes: Means not population-weighted

The estimates in column 1 come from an OLS regression between HHI and taxes per capita across cities. Column 2 adds the results of a fixed effects regression between HHI and tax revenues per capita. Column 3 displays the estimates of the OLS regression between system HHI and taxes. Column 4 exhibits the fixed effects results of system HHI and taxes. Columns 5 through 8 do the same for HHI and property taxes per capita.

Although the OLS regression across cities suggests a negative relationship between hospital concentration (HHI) and taxes per capita, the fixed effects model, which examines variation within a city and accounts for time effects, shows a positive and moderately significant relationship between HHI and taxes per capita: a 10% increase in HHI is associated with an approximately 1.6% increase in taxes per capita. Whereas the OLS regression captures that small cities tend to have concentrated hospital sectors and low rates of taxation, fixed effects indicate that an increase

<table>
<thead>
<tr>
<th>Table 2 – Effect of Hospital Concentration on Taxes and Property Taxes Per Capita</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log(Taxes Per Capita)</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>Pooled Fixed Effects</td>
</tr>
<tr>
<td>(1)</td>
</tr>
<tr>
<td>Log(HHI)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Log(System HHI)</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Fixed Effects: Yes
Observations: 2,058
$R^2$: 0.338

Note: *p<0.10; **p<0.05; ***p<0.01

Standard errors clustered by city and results weighted by city population.
in hospital concentration within a city is associated with a decrease in taxes per capita. Similarly, the movement from across-city variation to within-city variation flips the direction of the impact of system HHI on taxes per capita from negative to positive.

Though far from conclusive, the property tax results imply that HHI and property taxes per capita are positively correlated, with a 10% increase in HHI associated with a roughly 2% increase in property tax revenues. The correlation between system HHI and property taxes is slightly positive and statistically insignificant.

3. Heterogeneous Treatment Effects

In this section, I examine which types of cities are driving the relationship between hospital concentration and tax revenues. I find that cities with higher taxes, with higher nonprofit ownership shares, and that support their hospitals financially exhibit more substantial relationships between hospital concentration and taxes.

The relationship between HHI, on the one hand, and taxes and property taxes, on the other, is the most positive and most statistically significant in cities with the highest tax revenues. To determine which cities account for the relationship between HHI and taxes per capita, I take each city’s average tax revenue over the study period and then organize cities above and below the median average tax revenue over the study period. In Table 3, I test HHI’s relationship with taxes and property taxes above and below the median.

### Table 3

| Effect of HHI on Taxes by Whether Above or Below Median Tax Revenue Per Capita |
|-------------------------------|----------------------------------|----------------------------------|
|                              | Log(Taxes Per Capita)            | Log(Property Taxes Per Capita)    |
|                              | Below (1)                        | Above (2)                        |
|                              | Below (3)                        | Above (4)                        |
| Log(HHI)                     | -0.027                           | 0.204*                           |
| (0.061)                      | -0.054                           | 0.259*                           |
| Fixed Effects?               | Yes                              | Yes                              |
| Observations                 | 1,036                            | 1,022                            |
| R²                           | 0.849                            | 0.957                            |
| Note:                       | *p<0.10, **p<0.05, ***p<0.01     | Results weighted by population and standard errors clustered by city

Columns 1 and 2 of Table 3 display the results of my fixed effects regression of HHI and taxes per capita in below-median and above-median taxed cities, respectively. Columns 3 and 4 do the same for HHI and property taxes. In high-taxed cities, a 10% increase in HHI corresponds to a statistically significant 2% increase in taxes per capita. In cities with below-median taxation, the effect of HHI on taxes is slightly negative and statistically insignificant. Likewise, Table 3 shows that above-median taxed cities are powering the positive relationship between HHI and property taxes I observe in Table 3. In high-taxed cities, a 10% increase in HHI is associated with an approximately 2.6% increase in property taxes per capita. In less-taxed cities, HHI has no effect on taxes or property taxes. Treating taxes as an imperfect indicator of a city’s wealth or tax base—since cities with higher per capita incomes can afford to tax their residents more—Table 3 illustrates that hospital concentration has a larger impact on tax revenue in prosperous cities.

In the following analyses, I investigate whether a city’s share of nonprofit hospitals affects my treatment effects. In Table 4, I start by calculating the average of each city’s nonprofit ownership share over the study period and then divide cities into subsets depending on whether they are above or below the median city’s for-profit share, allowing me to discern whether cities with higher or lower nonprofit ownership account for the relationship between HHI and taxes.

### Table 4

| Effect of HHI on Taxes by Whether Above or Below Median Nonprofit Ownership Share |
|---------------------------------|---------------------------------|---------------------------------|
|                                | Log(Taxes Per Capita)           | Log(Property Taxes Per Capita)  |
|                                | Below (1)                      | Above (2)                      |
| Fixed Effects?                 | Yes                             | Yes                             |
| Observations                   | 812                             | 798                             |
| R²                             | 0.912                           | 0.981                           |
| Note:                         | *p<0.10, **p<0.05, ***p<0.01    | Results weighted by population and standard errors clustered by city

Though the share of nonprofit hospitals is not the inverse of the share of for-profit hospitals thanks to the existence of government-run hospitals, the results for nonprofit and for-profit hospitals mirror each other. Cities with a higher share of nonprofit hospitals exhibit a larger association between hospital concentration and taxes. In Table 4, the relationship between hospital concentration and taxes is statistically insignificant above and below the median nonprofit ownership share. However, the coefficient for HHI and taxes is seemingly more positive in cities with above-median nonprofit ownership shares, with a 10% increase in HHI corresponding to a 1.5% increase in above-median nonprofit cities. Likewise, HHI and property tax revenue per capita are more positively related in
cities with above-median nonprofit ownership shares: a 10% increase in HHI is associated with a roughly 3% increase in property tax revenue in cities with above-median nonprofit ownership.

Given that cities with higher tax revenues exhibit a larger association between hospital concentration and taxes, the extent to which cities direct revenue to hospitals may reinforce the relationship between city finances and hospital concentration. To explore whether city government spending patterns affect this relationship, I split cities in Table 5 by whether or not they have ever supported their hospitals financially through direct hospital payments.

### Table 5
Effect of HHI on Taxes by Whether Cities Financially Support Their Hospitals

<table>
<thead>
<tr>
<th></th>
<th>Support (1)</th>
<th>Don’t Support (2)</th>
<th>Support (3)</th>
<th>Don’t Support (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log(Taxes Per Capita)</td>
<td>0.170</td>
<td>0.098</td>
<td>0.205</td>
<td>0.114</td>
</tr>
<tr>
<td>(0.095)</td>
<td>(0.067)</td>
<td>(0.142)</td>
<td>(0.065)</td>
<td></td>
</tr>
<tr>
<td>Log(Property Taxes Per Capita)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed Effects?</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Observations</td>
<td>1,274</td>
<td>784</td>
<td>1,274</td>
<td>784</td>
</tr>
<tr>
<td>R²</td>
<td>0.969</td>
<td>0.940</td>
<td>0.919</td>
<td>0.952</td>
</tr>
</tbody>
</table>

Note: Standard errors clustered by city and results weighted by population

Columns 1 and 3 of Table 5 display my estimates for the relationship between HHI and measures of tax revenue for the 91 cities that financially supported their hospitals between 2001 and 2014. Columns 2 and 4 contain estimates for the 56 cities that never supported their hospitals. In cities that have supported their hospitals financially, a 10% increase in HHI is associated with a moderately significant 1.7% increase in taxes and a statistically insignificant 2% increase in property taxes. The relationship between HHI and taxes per capita in cities that have never supported their hospitals financially is both statistically insignificant and less positive, with a 10% increase in HHI resulting in a statistically insignificant 1% increase in taxes and a statistically significant 1.1% increase in property taxes. Thus, the relationship between HHI and tax revenues appears largest in cities that have supported their hospitals financially than within those that have not.

These results reveal that the effect of HHI on taxes and property taxes is stronger in some cities than in others. In cities with higher tax revenues per capita, my results point to a statistically significant, positive relationship between HHI, on one side, and taxes and property taxes, on the other. In cities with a higher nonprofit hospital share and lower for-profit hospital ownership share, HHI and tax revenues are more positively related. Finally, in cities that support their hospitals financially, the relationship between HHI and tax revenues is more positive.

These findings are likely interdependent since cities with lower for-profit shares also tend to have higher taxes, the OLS results in Tables 6 and 7 show. Cities with higher tax revenues are more likely to spend across a wide variety of items, including direct payments to hospitals. That the relationship between hospital concentration and municipal finances is strongest in cities with higher taxes, lower for-profit shares, and higher spending on hospitals may stem from these cities having more mechanisms through which hospital concentration can affect municipal finances. In a city with low tax revenues and low spending, it is possible that any change in the relative concentration of that city’s hospital sector is less likely to influence its finances because the city lacks the mechanisms, including direct hospital payments, to register such a change.

### 4. Mechanisms

In this section, I attempt to identify a mechanism through which hospital concentration impacts city taxes. The two mechanisms I explore are: (1) changes in the share of for-profit, nonprofit, or government hospitals and (2) changes in hospitals’ capital expenditures. For the first, it is possible that growth in the for-profit hospital share could increase tax revenues since cities can tax for-profit hospitals. For the second, growth in hospitals’ capital expenditures could signal that hospitals are purchasing land or building new facilities, which could alter a city’s property tax base. If a nonprofit hospital buys land, for example, a city’s property tax base would contract because it cannot tax land owned by nonprofits. Since 30% of cities’ tax revenues come from property taxes in 2017, according to the Tax Policy Center, any change, including hospital ownership status, that affects a city’s property tax base could have a measurable impact on its revenue generation. I fail to find supporting evidence for either mechanism. Only the government hospital share has a positive and statistically significant effect on taxes, while the shares of nonprofit and for-profit hospitals have negligible impacts. Instead of finding an association between capital expenditures and tax revenues, my estimates imply that capital expenditures correspond to a decrease in hospital concentration and are not significantly related to tax revenue.

Because nonprofit hospitals are exempt from property taxes, it is worth exploring whether growth in the nonprofit hospital sector impacts municipal finances.
this, I run city fixed effects regressions of RAND’s measures of nonprofit, for-profit, and government ownership on tax data taken from the Lincoln Institute in Table 6.

<table>
<thead>
<tr>
<th>Table 6 – Effect of Hospital Ownership on Taxes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent variable: LogTax Revenue Per Capita</td>
</tr>
<tr>
<td>Pooled OLS (1) Fixed Effects (2) Pooled OLS (3) Fixed Effects (4) Pooled OLS (5) Fixed Effects (6)</td>
</tr>
<tr>
<td>Percent Nonprofit 0.306 -0.032 (0.334) (0.064)</td>
</tr>
<tr>
<td>Percent For-Profit -0.580 -0.081 (0.482) (0.082)</td>
</tr>
<tr>
<td>Percent Government 0.193 0.223* (0.213) (0.105)</td>
</tr>
<tr>
<td>Fixed Effects? No Yes No Yes No Yes Observations 1,610 1,610 1,610 1,610 1,610 1,610</td>
</tr>
<tr>
<td>R² 0.029 0.965 0.065 0.965 0.003 0.965</td>
</tr>
</tbody>
</table>

Note: *p<0.10**p<0.05***p<0.01 Standard errors clustered at the city level and results weighted by population

Columns 1 and 2 of Table 6 present results from an OLS and a city fixed effects regression, respectively, of nonprofit ownership share on tax revenue per capita. Columns 3 and 4 do the same for the share of for-profit hospitals on taxes. Columns 5 and 6 add the results of the relationship between government-run hospitals and taxes. Growth in the nonprofit or for-profit market share has a negligible impact on tax revenue. Only the share of government-run hospitals is statistically significantly associated with tax revenue per capita: a 10% increase in the government share corresponds to an approximately 2.2% increase in tax revenues within a city. This may be a case of reverse causality, though: to operate government-run hospital systems, governments need more revenue.

Because nonprofit hospitals are exempt from property taxes, it is possible that nonprofit and for-profit consolidation have divergent effects on property tax revenue. Hence, the negative coefficient of for-profit hospital ownership on property taxes is surprising.

As Table 7 illustrates, growth in the market share of for-profit hospitals within a city is associated with a statistically significant decrease in property taxes per capita. I found that a 10% increase in the for-profit share corresponds to a decrease in property taxes of roughly 2.3%. Because cities can tax land owned by for-profit hospitals, growth in the for-profit share may expand a city’s property tax base. With a broader tax base, a city’s tax burden may be spread more evenly across the population, possibly resulting in lower property taxes per capita. Growth in the nonprofit share of hospitals within a city has virtually no impact on property tax revenues. A 10% increase in the government ownership share, by contrast, increases property tax revenue by approximately 4.2%, a result that is statistically significant at the 1% level. This, too, is likely a case of reverse causality: to fund government hospital systems, cities need higher property taxes. It is worth noting that growth in the for-profit hospital share has a significantly more negative effect on property tax revenues than does an increase in the nonprofit hospital share.

Additionally, with the RAND dataset, I examined whether HHI affected capital expenditures, which could suggest that consolidation breeds construction. I next checked whether increases in capital expenditures within a city impacted tax revenues. If hospital concentration were expanding construction and construction were then raising tax revenues by increasing property values or incomes, then I could identify a possible causal mechanism.

<table>
<thead>
<tr>
<th>Table 7 – Effect of Hospital Ownership on Property Taxes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent variable: Log(Property Tax Revenue Per Capita)</td>
</tr>
<tr>
<td>Pooled OLS (1) Fixed Effects (2) Pooled OLS (3) Fixed Effects (4) Pooled OLS (5) Fixed Effects (6)</td>
</tr>
<tr>
<td>Percent Nonprofit 0.013 -0.009 (0.219) (0.102)</td>
</tr>
<tr>
<td>Percent For-Profit -0.128 -0.226* (0.294) (0.115)</td>
</tr>
<tr>
<td>Percent Government 0.232 0.418*** (0.272) (0.158)</td>
</tr>
<tr>
<td>Fixed Effects? No Yes No Yes No Yes Observations 1,610 1,610 1,610 1,610 1,610 1,610</td>
</tr>
<tr>
<td>R² 0.0001 0.924 0.004 0.924 0.006 0.925</td>
</tr>
</tbody>
</table>

Note: *p<0.10**p<0.05***p<0.01 Standard errors clustered at the city level and results weighted by population

<table>
<thead>
<tr>
<th>Table 8 – Effect of HHI/System HHI on Measures of Capital</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent variable: Log(Capital-Related Buildings and Fixtures) + Log(Capital-Related Costs) + Log(Total Fixed Assets)</td>
</tr>
<tr>
<td>Pooled OLS (1) Fixed Effects (2) Pooled OLS (3) Fixed Effects (4)</td>
</tr>
<tr>
<td>Log(HHI) -3.888*** (0.233) -3.832*** (0.335)</td>
</tr>
<tr>
<td>Log(System HHI) -5.314*** (0.448) -0.547 (0.418)</td>
</tr>
<tr>
<td>Fixed Effects? No Yes No Yes Observations 1,593 1,593 1,593 1,593</td>
</tr>
<tr>
<td>R² 0.745 0.988 0.758 0.987</td>
</tr>
</tbody>
</table>

Note: *p<0.10**p<0.05***p<0.01 Standard errors clustered at the city level and results weighted by population
On the first count, Table 8 shows that HHI is associated with reductions in hospital capital, a combination of capital-related buildings and fixtures, total fixed assets, and capital-related costs.

Columns 1 and 2 of Table 8 feature OLS and fixed effects regression results of HHI on measures of hospital capital. Columns 3 and 4 do the same for system HHI and measures of capital. As the fixed effects results in Table 8 illustrate, a 10% increase in HHI within a city corresponds to a significant 8.3% decrease in various measures of capital. Likewise, increases in system consolidation appear to be weakly associated with falling capital costs within a city.

When I separate these measures of capital in Table 9, I also find that HHI reduces capital costs and expenditures.

### Table 9 - Effect of HHI/System HHI on Capital-Related Costs

<table>
<thead>
<tr>
<th>Dependent variable:</th>
<th>Pooled OLS (1)</th>
<th>Log(Capital-Related Costs)</th>
<th>Fixed Effects (2)</th>
<th>Pooled OLS (3)</th>
<th>Fixed Effects (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log(HHI)</td>
<td>-1.341***</td>
<td>-0.395***</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.106)</td>
<td>(0.119)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log(System HHI)</td>
<td></td>
<td></td>
<td>-1.822***</td>
<td>-0.153</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.193)</td>
<td>(0.162)</td>
<td></td>
</tr>
<tr>
<td>Fixed Effects?</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Observations</td>
<td>1,593</td>
<td>1,593</td>
<td>1,593</td>
<td>1,593</td>
<td></td>
</tr>
<tr>
<td>R²</td>
<td>0.739</td>
<td>0.980</td>
<td>0.741</td>
<td>0.980</td>
<td></td>
</tr>
</tbody>
</table>

Note: *p<0.10 †p<0.05 ‡p<0.01
Standard errors clustered at the city level and results weighted by population

With a statistical significance of less than 1%, a 10% increase in HHI is associated with a 4% decrease in capital-related costs. Though statistically insignificant, growth in system HHI also appears to reduce capital-related costs.

Together, Tables 8 and 9 demonstrate that HHI has a significantly negative impact on capital expenditures and costs.

On the second count, however, Table 10 identifies no significant relationship between various measures of capital expenditures and taxes or property taxes.

The estimates in columns 1 and 2 come from OLS and fixed effects regressions, respectively, of measures of capital costs and expenditures and taxes per capita. Columns 3 and 4 do the same for fixed measures on property taxes. None of the estimates is large or statistically significant.

Columns 1 and 2 display the results of fixed effects regressions of HHI on taxes per capita without and with capital controls, respectively. Columns 3 and 4 add the results for property taxes without and with capital controls. Unlike Table 2, I find no statistically significant relationship between HHI and taxes or property taxes in Table 11. However, like my previous results, Table 11 highlights a positive, though statistically insignificant, relationship between HHI and the two measures of tax revenue. More importantly, adding capital controls hardly budges my

### Table 10 - Effect of Capital Asset Building Improvements Depreciated on Taxes & Property Taxes

<table>
<thead>
<tr>
<th>Dependent variable:</th>
<th>Log(Taxes Per Capita)</th>
<th>Log(Property Tax Per Capita)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pooled OLS (1)</td>
<td>Fixed Effects (2)</td>
</tr>
<tr>
<td>Log(Capital-Related Buildings and Fixtures)</td>
<td>-0.103</td>
<td>-0.028</td>
</tr>
<tr>
<td>Log(Capital-Related Costs)</td>
<td>(0.073)</td>
<td>(0.028)</td>
</tr>
<tr>
<td>Log(Total Fixed Assets)</td>
<td>0.277***</td>
<td>0.064</td>
</tr>
<tr>
<td></td>
<td>(0.124)</td>
<td>(0.025)</td>
</tr>
<tr>
<td></td>
<td>0.045</td>
<td>-0.018</td>
</tr>
<tr>
<td></td>
<td>(0.061)</td>
<td>(0.025)</td>
</tr>
<tr>
<td>Fixed Effects?</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Observations</td>
<td>1,593</td>
<td>1,593</td>
</tr>
<tr>
<td>R²</td>
<td>0.615</td>
<td>0.965</td>
</tr>
</tbody>
</table>

Note: *p<0.10 †p<0.05 ‡p<0.01
Standard errors clustered at the city level and results weighted by population

To further investigate whether changes in capital expenditures act as a causal mechanism for hospital concentration to affect taxes and property taxes, I add capital controls—the logarithms of capital-related buildings and fixtures, capital-related costs, and total fixed assets—to my fixed effects regression, in Table 11. Because only the RAND dataset contains measures of capital, the results in Table 11 are not directly comparable to those in Table 2 based on the Lincoln data.

### Table 11 - Effect of HHI on Taxes/Property Taxes Without and With Controls

<table>
<thead>
<tr>
<th>Dependent variable:</th>
<th>Log(Taxes Per Capita)</th>
<th>Log(Property Tax Per Capita)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Controls (1)</td>
<td>Controls (2)</td>
</tr>
<tr>
<td>Log(HHI)</td>
<td>0.139</td>
<td>0.134</td>
</tr>
<tr>
<td></td>
<td>(0.108)</td>
<td>(0.104)</td>
</tr>
<tr>
<td>Capital Controls?</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Observations</td>
<td>1,610</td>
<td>1,593</td>
</tr>
<tr>
<td>R²</td>
<td>0.966</td>
<td>0.966</td>
</tr>
</tbody>
</table>

Note: *p<0.10 †p<0.05 ‡p<0.01
Standard errors clustered at the city level and results weighted by population
fixed effects results and standard errors, signaling that changes in capital expenditures do not explain the positive association between hospital concentration and taxes. Although I was unable to conclusively identify a mechanism to explain the positive relationship between HHI and taxes per capita, I can rule out two hypotheses. The first hypothesis which my analysis could not corroborate was that hospital ownership status was responsible for the positive relationship between hospital concentration and tax revenues within a city. The second hypothesis that we can discard is that, as hospitals invested in making improvements and purchased more real estate, they drove up property values and thereby increased property tax revenues. Instead, I found no significant relationship between various measures of capital construction and tax revenues. Simultaneously, I found a significantly negative relationship between hospital concentration and capital costs, indicating that increases in HHI may stem from closing competitor hospitals, which would decrease the footprint of hospitals in a city, or that hospitals, contrary to industry claims, invest less on capital improvements in the wake of consolidation. Future research might untangle through which mechanism growth in HHI is connected to decreases in capital expenditures.

CONCLUSION

Using city fixed effects regressions on hospitals and municipal finances in 147 American cities from 2001 to 2014 and controlling for time effects, I found a statistically significant relationship between hospital concentration and tax revenues per capita within cities. A 10% increase in hospital concentration was associated with an approximately 1.6% increase in tax revenues per capita within a city. Although statistically insignificant, HHI and property tax revenue per capita appear to be positively correlated, with a 10% increase in HHI associated with a 2% increase in property tax revenue per capita.

Since adoption of the Affordable Care Act, hospital systems have driven the nationwide trend in hospital consolidation, according to Cooper et al. (2019). Nevertheless, compared to the relationship between HHI and taxes, that between system HHI and taxes within cities over time is weak. With a correlation of 0.93, HHI and system HHI are similar variables. Whereas HHI measures market concentration across individual hospitals within a city, system HHI measures market concentration across hospital systems within a city. That HHI has a stronger relationship with taxes than system HHI may be a sign that growth in hospital size as measured by beds, not hospital system consolidation, is responsible for the association between hospital concentration and municipal finances.

Through my heterogeneous treatment effects analysis, I determined that cities with higher tax bases and those that supported their hospitals financially exhibited stronger positive relationships between hospital concentration and tax revenues per capita, reinforcing the idea that cities with higher taxes and cities that spend on a broader scale are more likely to register changes in hospital concentration than those with low taxes and low spending. My investigation of two possible mechanisms through which hospital concentration could impact municipal tax revenues—first, changes in ownership status and, second, changes in capital costs and expenditures—came up empty. Lacking concrete evidence of a mechanism, I am reluctant to declare that hospital concentration causes tax revenues per capita to increase within a city. However, my results suggest that changes in tax revenue are associated with changes in hospital consolidation within a city. Future research should investigate possible mechanisms for the relationship between hospital concentration and taxes, potentially confirming a causal relationship, and investigate why hospital concentration correlates to reductions in capital costs and expenditures.

REFERENCES

1. Data Sources


2. Literature Review Documents


Altering sensory learning by chronic inactivation of VIP interneurons

Christopher Alba1, Hannah Selwyn1, Katie A. Ferguson2, Jessica A. Cardin2,3
1Department of Molecular, Cellular and Developmental Biology, Yale University, 2Department of Neuroscience, Yale University, 3Kavli Institute for Neuroscience, Yale University

ABSTRACT

Vasoactive intestinal polypeptide-expressing interneurons (VIP-INs) play a key role in the regulation of cortical circuits and are implicated in perceptual function and psychiatric disease. However, their role in perceptual augmentation and learning remains understudied. We performed chronic, localized ablation of VIP-INs in the primary visual cortex of adult mice using caspase-induced apoptosis to better understand how VIP-INs contribute to visual perception and the ability to learn a visual detection task. We find that chronic VIP-IN ablation does not affect naïve performance on a full-screen visual contrast detection task. However, mice with suppressed levels of VIP-INs achieved their final expert state more rapidly and exhibited a greater detection advantage during high-arousal compared to control mice. These results suggest VIP-INs have an important role in modulating the learning process of cortical networks in the primary visual cortex.

INTRODUCTION

Sensory processing in the brain is finely controlled by both excitatory and inhibitory networks in the cerebral cortex. The activity of inhibitory GABAergic interneurons (INs) help shape how information is integrated by excitatory neurons in a context- and behavior-specific way. Three major classes of INs have been identified as prominent contributors to inhibition in neocortical circuits: parvalbumin-positive (PV) cells, somatostatin-positive (SST) cells, and vasoactive intestinal polypeptide-positive (VIP) cells ( Tremblay et al., 2016 ). Beyond their significance in cortical function, dysfunctional GABAergic INs have also been correlated with cognitive and neurologic disorders such as epilepsy, schizophrenia, anxiety, and autism ( Fishell & Rudy, 2011, Mossner et al., 2020 ). Insight into the roles of GABAergic INs in the cortex may ultimately help elucidate their contributions to these neurologic disorders.

The connectivity of IN classes has been established through anatomical and functional studies. PV- and SST-INs directly inhibit excitatory pyramidal cells through perisomatic and distal dendritic synapses, respectively ( Rudy et al., 2010; Atallah et al., 2012; Cottam et al., 2013; Glickfeld et al., 2013; Kubota et al., 2016, Cone et al., 2019). In contrast, VIP-INs primarily inhibit SST-INs, leading to disinhibition of excitatory cells ( Pfeffer et al., 2013; Pi et al., 2013; Fu et al., 2014; Karnani et al., 2016; Garcia-Junco-Clemente et al., 2017; Cone et al., 2019). While advancements have been made in understanding the role of GABAergic INs as a whole on cortical activity, their heterogeneous responses to stimuli within subclasses ( Khan et al., 2018 ) have made their unique contributions to sensory processing difficult to fully characterize.

The visual cortex—where PV-, SST-, and VIP-INs make up 80% of the IN population ( Pfeffer et al., 2013 )—presents a unique opportunity to better understand the varied inhibitory IN subtypes due to the ability to simultaneously investigate sensory processing, perception, and cognition. By studying animal models engaged in perception tasks, the largely unexplored effect of IN manipulation on sensory perception can be identified. The few existing studies using optogenetic activation or suppression of VIP-INs have demonstrated both increased and decreased activity of the surrounding local network ( Ayzenshtat et al., 2016; Cone et al., 2019). These differing results are likely due to vastly different ways of stimulating interneurons, such as differing power and frequency of the optogenetic manipulation. Furthermore, optogenetic manipulation only transiently activates or suppresses activity, a characteristic that makes it difficult to study the long-term effects of IN-specific activation or suppression on perceptual learn-
Perceptual learning refers to long-lasting changes to an organism’s cortical network that improves its ability to respond to its environment by using previously unused information (Gibson and Gibson, 1955; Goldstone, 1998). Improved performance on visual tasks has been attributed to improvements in the existing cortical network’s ability to reweight its sensory inputs after task-relevant training (Dosher and Lu, 2017). Chronic disruption of VIP-INs using gene deletion early in development impaired contrast perception and disrupted perceptual learning at low-contrast visual stimuli (Batista-Brito et al., 2017). However, gene deletion early in development may have confounding effects from circuitry compensatory mechanisms. Given the mixed literature on VIP-INs, further research is needed to identify the role of VIP-INs in visual perception and learning.

The chronic local removal of VIP-INs in the primary visual cortex (V1) of adult mice may shed insight on the normal function of VIP-INs in perception and perceptual learning, a difficult challenge to solve using only acute optogenetic approaches. We found that chronic ablation of VIP-INs using selective caspase-induced apoptosis in the adult mouse visual cortex led to faster perceptual learning and improved final steady-state performance during arousal. Our results suggest that task performance using small visual stimuli may be particularly sensitive to these effects.

MATERIALS AND METHODS

Experimental animal model

All animal handling and maintenance was performed in accordance with the regulations set by the Yale University School of Medicine Institutional Animal Care and Use Committee. Transgenic mouse lines were crossed to produce VIP-Cre<sup>+/0</sup>/Ai9<sup>+/0</sup> reporter animals. Both male and female mice were used.

Caspase injection and headpost surgery

Genetically engineered caspase was used to selectively deliver caspase to molecularly defined VIP-INs in the visual cortex (Yang et al., 2013). Using an aseptic technique, anesthetized adult mice were bilaterally injected with 1 μl of caspase virus (rAAV5/Flex-taCasP3-TEVP, ~10<sup>12</sup> viral particles) or 0.9% saline in V1 at a depth of 350 μm beneath the pial surface and a rate of 0.060 μl/min. After injection, the skull surface was sanitized and mice were implanted with an adhesive cement (C&B Metabond, Parkell) headpost stabilized by a skull screw (McMaster-Carr) placed in the anterior pole. Two nuts (McMaster-Carr) were placed within the cement headpost to allow for headpost fixing during behavioral experiments. Mice were given 3-5 days following surgery to recover prior to wheel and task training.

Wheel training and visual detection task

Mice were headposted in place with a natural running head angle on top of a circular wheel. Mice were headposted daily for increasing intervals until they exhibited consistent running bouts throughout a 60-minute session (~8-10 days) as measured by a wheel sensor. Mice were also placed on a water-controlled schedule with careful weight monitoring. Once mice stabilized to 83-86% of their starting weight and exhibited consistent running bouts, mice were trained on a GO/NOGO contrast visual detection task (Figure 1A). Mice were first trained to respond by licking to a full-screen shifting vertical grating (contrast = 100%, spatial frequency = 0.05 cycles per degree, temporal frequency = 2 Hz, duration = 1 second) and were rewarded with a 3 μl water droplet upon successful detection.

![Figure 1. Schematic of visual detection task.](image-url)

(A) Water-deprived mice were trained to respond by licking upon detection of a full-screen shifting vertical grating stimulus. Detection results in a water delivery allowed to run freely on wheel. Tasks are run for 45 mins/day for 10-15 days. (B) The stimulus begins with the presentation of a grating for 1 second. Mice have 1 second to respond to the visual stimulus following a 0.5 second delay following stimulus onset.
tion of the grating stimulus within 2 seconds of stimulus presentation (Figure 1B). Incorrect hits were followed by a time out (Figure 1A). Inter-trial intervals were randomly varied using an exponential distribution with a flat hazard rate. Mice were trained until they achieved a correct hit rate of at least 95% and a maximum false alarm rate of 10% (~5-10 days). They were then placed on the visual detection task of interest with a full-screen shifting vertical grating of varying contrasts (0.35%, 0.5%, 0.75%, 1%, 2%, 5%, 10%, 20%, and 100%) for 10-15 days. The visual detection task was based on one used in a previous study (Batista-Brito et al., 2017). Given that surgical recovery and behavioral task training takes approximately 22-35 days in total, all mice used for behavioral experiments began the varying contrast detection task no earlier than 22 days following injection. Training timepoints were chosen to allow for learning and ensure the caspase virus could achieve full ablation (Figure S1).

Behavioral data analysis

All quantitative analysis of perceptual performance data was performed using MATLAB. For each session, we constructed psychometric performance curves using a sigmoid function based on the hit rate (HR) at each contrast. The true hit rate was found by correcting for the false alarm rate (FAR) per session (HR_{true} = (HR_{observed} - FAR) / (1 – FAR)). Sessions were removed from the analysis if the median FAR at the two lowest contrasts (0.35% and 0.5%) exceeded 50% or if the median HR at the highest contrast (100%) was below 75%. Additionally, all sessions were required to have at least 50 trials for inclusion. Complete task disengagement at the end of a session was identified and removed, as well as intra-session bouts of task disengagement indicated by 10 subsequent trials of inactivity. Performance was separated by arousal state indicated by quiescence or any duration of locomotion during a visual stimulus trial. The psychometric performance curve per day per mouse was constructed by bootstrapping the trials per session. We used a hierarchical bootstrapping approach (Saravanan, Berman, and Sober, 2019) to produce summary data. To do so, we created 5,000 new datasets by resampling with replacement first at the level of animals followed by trials within a session. We then computed the mean across all trials for each contrast for each resampled data set. The final statistic is computed on this population of resampled means. Resampled hit rates were compared by calculating the probability that resampled hit rates were greater than a specified day (over time comparisons) or greater for caspase mice compared to control mice (between experimental group comparisons). To track perceptual learning, the parameters used to plot the performance curves were also used to analyze the change over time in: 1) the contrast needed to achieve 50% detection (C_{50}), and 2) the change in true hit probability at a given contrast.

RESULTS

Caspase-induced apoptosis selectively ablated VIP-INS in V1

We confirmed the efficacy of injecting 1 μl of caspase virus in a subset of the mice used for behavioral experiments (n = 4/8 caspase mice, n = 4/8 control mice) ex-vivo. Cell density in most mice was comparable to values seen during a previous caspase efficacy and time course study (Supplemental Methods, Figure S1) and were not significantly different between the hemispheres of each mouse (student’s t-test per mouse, p > 0.10; Figure 2A). In general, caspase mice had significantly reduced VIP cell density (ρ_{avg, caspase} = 16.6 vs. ρ_{avg, control} = 235.1; unpaired student’s t-test, p < 0.001; Figure 2B). While a histological analysis on the full cohort of behavioral mice could not be conducted due to COVID-19 interruptions, the partial histological dataset shows selective VIP-IN ablation occurred at levels consistent with the findings from the experimental method validation study (Figure S1).

VIP-ablation enhanced the perceptual learning timeline

Generally, all mice demonstrated improved task performance by maintaining detection of high contrasts and learning to respond to low contrasts over time. This trend is indicated by a leftward shift in the psychometric performance curve (Figure 3). Detection of 1% and 10% contrasts was not significantly different between early and
late days for controls (day 1 > day 8, p = 0.59 and 0.29, respectively) and caspase mice (day 1 > day 8, p = 0.29 and 0.20, respectively) (Figure 4A). Mice did improve their detection of 2% contrast gratings over time (day 1 > day 8, p = 0.09 (control), <0.001 (caspase); Figure 4A). However, detection of 2% contrast did not exceed detection by chance (50% detection) for either group after day 7. Perception of stimuli was comparable between groups during the early phase of learning (days 1 and 2). There was no significant difference between controls and caspase-injected mice in early detection of 2% and 5% contrasts (probability of resampled caspase means being greater than or equal to control means was p = 0.6832 and 0.6909, respectively) (Figure 4B). Arousal, as indicated by locomotion, improved detection of stimuli comparably between groups (Figure 5A). During the middle phase of learning (days 4 and 5), caspase mice exhibited increased detection of the 2% contrast grating compared to control mice. A caspase advantage at 2% contrast is seen in 92.36% of all paired hierarchical bootstrapping mean hit rates (Figure 4C). Improved performance during the middle phase of learning was driven by improved detection during times of locomotion (Figure 5B). During the late phase of learning (days 8 and 9), the bootstrapped hit rates of caspase and control mice reflected unity (Figure 4D). Small but insignificant improvements in late performance during locomotion were made by both groups compared to that during the middle phase (Figure 5C). However, late phase caspase mice performance during quiescence significantly decreased compared to that of the middle phase (Figure 5C). Overall, learning appeared to occur faster in caspase mice as indicated by a significant leftward shift (caspase middle vs. early performance, p < 0.01) in the 3-day average psychometric performance curve during locomotion in the middle phase of learning.

Figure 2. Successful ablation of VIP-INs in mice used for behavioral experiments. (A) To verify the success of caspase-induced cell death in mice used for behavioral experiments, brain tissue was fixed, sectioned, and imaged. Average VIP cell density (per mm2) were computed within each hemisphere of experimental mice using 2 to 3 subsequent coronal sections of V1. Mice injected with caspase are depicted in red (n = 4) while those injected with saline are depicted in blue (n = 4). Error bars depict the SD in each hemisphere. Unpaired Student’s t-tests were used to determine significant differences in cell density between the two hemispheres of each mouse (n.s. = p-value > 0.10). The dashed blue and red lines demarcate the mean VIP cell density expected following 21 days of saline or caspase incubation, respectively. Cell counts for n = 4 caspase mice and n = 4 control mice were not conducted due to COVID-19 interruptions. (B) Box and whiskers plot showing the 10-90th percentile of VIP cell density found in mice used in behavioral experiments (n = 4 caspase, n = 4 control). Cell counts below the 10th percentile and above the 90th percentile are indicated by single dots. The dashed blue and red lines demarcate the mean VIP cell density expected following 21 days of saline or caspase incubation, respectively. Unpaired students’ t-tests were used to determine a significant difference in cell density between caspase and control mice (** = p-value < 0.001).

Figure 3. Psychometric performance curves of a single mouse across multiple days. Mice were run daily on a visual detection task of varying contrasts (0.35%, 0.5%, 0.75%, 1%, 2%, 5%, 10%, 20%, and 100%). Psychometric performance curves were created by bootstrapping the trials per mouse and per day fit to a sigmoid function. Hit rates underwent data cleaning and false alarm correction. Individual hit rates are shown using markers color-coded by the task day. The contrast at which the gray dashed line and the psychometric curve intersect is the contrast at which the mouse detects the stimulus in 50% percent of trials (C_{50}). Movement of the C_{50} to lower values is generally noted within each mouse as an indicator of perceptual learning.
with diminished VIP-IN density exhibit an enhanced rate of perceptual learning and improved perception during arousal compared to control mice.

The $C_{50}$ value is an indicator of the lowest contrast at which a mouse is able to detect a stimulus with a greater than chance probability. The $C_{50}$ value is extrapolated from the measured hit rates using the psychometric performance curves. All mice in the caspase and control groups achieved a reduction in their $C_{50}$ during the task (Figure 6A), suggesting improved performance. Some mice exhibited increments in their $C_{50}$ during later days and were not included in the analysis of days thereafter. Given that most mice ($n = 4/8$ control, $n = 6/8$ caspase) met exclusion criteria (see Materials and Methods) by day 9, $C_{50}$ analyses were focused on days 1-8. The control group demonstrated moderate $C_{50}$ reductions through day 6 (31.9% reduction achieved), while the caspase group demonstrated $C_{50}$ reductions through day 8 (80.6% reduction achieved) (Figure 6A). We found that of mice that did not exhibit chronic task exhaustion, mice with VIP-ablation showed greater percentage reductions in $C_{50}$ suggesting improved task performance compared to their control counterparts (Figure 6A). Similarly, as a raw change in $C_{50}$ compared to day 1 performance, the caspase group achieved a larger maximum decrease in $C_{50}$ ($\Delta_{\text{caspase}} = -0.321$ vs. $\Delta_{\text{control}} = -0.200$) in a shorter time period ($\text{time}_{\text{caspase}} = 6 \text{ days}$ vs. $\text{time}_{\text{control}} = 8 \text{ days}$) compared to the control group (Figure 6B). However, it is difficult to determine the precise timing of when the learned steady-state was achieved given that the sampled group reduced in size during later days due to high false alarm rates (see Materials and Methods). Generally, the data suggest that of mice that do not expe-

Figure 4. Comparing the perception of low contrast stimuli over time between types of experimental mice. (A) Hierarchical bootstrapping was conducted by creating 5,000 datasets constructed by resampling at the level of animals followed by trials of a given day. The mean hit rate at each contrast was computed. The mean hit rate at 1, 2, 5, and 10% contrasts is graphed over time per experiment type. Mice injected with caspase and saline are indicated by the red and blue lines, respectively. Error bars indicate the SEM. (B-D) The joint probability distributions of VIP-ablated and control mice for the early (Day 1 and 2), middle (Day 4 and 5), and late (Day 8 and 9) phases of learning were plotted to compare the hit probability at 2% and 5% contrasts. The red percentage value indicates the percentage of paired trials in which VIP-ablated mice performed better than control mice at the given contrast and stage of learning.
perience task exhaustion, caspase mice make faster and larger reductions in $C_{50}$ relative to control mice. This further supports that mice with localized chronic VIP-IN ablation experience enhanced perceptual learning.

**VIP-ablation has similar enhancing effects on the performance of a small stimulus task**

After completion of the full-screen visual detection task, a small cohort of mice ($n = 2$ caspase, $n = 2$ control) were retrained for detection of a smaller circular grating (20° azimuth) in an exploratory experimental extension to test the robustness of our findings to stimulus design (Supplemental Methods, Figure S2). Task performance generally improved among both groups of mice with psychometric curves resembling those of the large stimulus task (Figure S2). Overall, VIP-ablation appears to enhance perception and perceptual learning of a small stimulus task compared to control mice (Figure S2). The enhanced perception of lower contrasts (~5%) is lasting throughout the duration of task learning (Figure S2). Despite the small sample size, this extension demonstrates our findings are likely robust to stimulus size.

**DISCUSSION**

We have shown that localized chronic ablation of VIP-INs through caspase-induced apoptosis does not affect naïve (early) performance on a full-screen visual detection task. However, mice with suppressed levels of VIP-INs achieved their final expert state more rapidly than control mice and exhibited better performance during locomotion. We further explored the effect of localized VIP ablation on the performance of mice on a small stimulus task, and found similar enhancing effects on both perception and learning. These results suggest VIP-INs have an important role in modulating the learning process of cortical networks in the primary visual cortex.

Our approach of chronic ablation in adult mouse V1 allowed us to identify the importance of VIP-INs in perception and learning. Recent literature has focused on optogenetic activation or suppression which only produces a transient effect (Ayzenshtat et al., 2016; Cone et al., 2019). While helpful in elucidating the online role of VIP-INs in perception, optogenetic approaches make studying chronic suppression or heightened activation more likely than transient suppression and activation outside of the lab setting.

We found that the chronic ablation of VIP-INs does not affect performance at high contrasts (>10%) during any segment of the learning timeline. Given VIP-IN activity is normally suppressed below baseline in response to high contrast gratings in all directions (Millman et al., 2019), this makes intuitive sense. However, our finding that VIP-ablation resulted in mice improving their detection of low contrast stimuli (2% and 5% contrasts) faster than control mice is in opposition to the existing literature, albeit limited. One study finds that dysregulation of VIP-INs through ErBB4 gene deletion in early develop-

![Figure 5. Psychometric performance curves of control and caspase mice over time by arousal state.](image-url)
Figure 6. Comparing perceptual learning using $C_{50}$ values as an indicator of performance.

(A) The contrast at which mice detect 50% of trials ($C_{50}$) is plotted for each individual mouse. The $C_{50}$ value at each day is a 2-day moving average and normalized as a percentage change from the $C_{50}$ on Day 1. Traces for individual mice are separated into section delimited by dashed lines and begin at 0% on Day 1. Individual sessions were removed based on a high false alarm rate at low contrasts or low hit rate at high contrasts (Materials and Methods). The sample size for caspase mice ($N_{caspase}$) and control mice ($N_{control}$) is indicated in red and blue, respectively.

(B) The change in $C_{50}$ compared to Day 1 performance is presented in units of log10(%) contrast and averaged using a 2-day moving average by experimental type (caspase in red and control in blue). Mice were removed from a given day based on a high false alarm rate at low contrasts or low hit rate at high contrasts (Materials and Methods). The hit probabilities achieved by the control mice at low contrasts reported in Batista-Brito et al. (2017) (near 100% hit rate for 1-2% contrasts) were much higher than in our experiments (under 50% detection). One explanation for these discrepancies may lie in key differences in their task design, such as the presentation of gratings in multiple directions and the use of a tone to cue the onset of a trial. The converse of our finding, that VIP-IN activation impairs performance on a visual task is also opposed by the literature. One study found that optogenetic activation of VIP-INs improved contrast increment detection (Cone et al., 2019). However, activation and inactivation of the same neuronal class has been found to not produce consistent insights (Phillips and Hassenstaub, 2016). As such, our use of chronic ablation as opposed to transient activation may explain our seemingly conflicting results.

One possible explanation of our results is that chronic VIP-IN ablation shifted the tuning of excitatory pyramidal cells to a spatial frequency aligned with the one used in our behavioral task (0.05 cycles/degree). One study found that optogenetic suppression of VIP-INs resulted...
in a stronger network response to stimuli of lower spatial frequencies (Ayzenshtat et al., 2016). If the overall network favored a frequency higher than 0.05 cpd at normal baseline, a shift toward our lower task-specific spatial frequency may explain the improved performance of the caspase mice.

A second explanation relies on the fact that locomotion generally increases neural responses in both broad- and narrow-spiking cells (Niell and Stryker, 2010). More specifically, locomotion increases pyramidal cell activity (Niell and Stryker, 2010; Ayaz et al., 2013; Fu et al., 2014, Millman et al., 2019). Consistent with this literature, our findings indicate that locomotion improves performance of a visual contrast detection task at all phases of learning. In general, the group of caspase mice engaged in locomotion more so than the control group according to preliminary data. The increased arousal-state of caspase mice may have resulted in greater pyramidal cell gain even at low contrasts compared to control mice. However, recent studies have found that chronic VIP-IN activity disruption eliminates the visual response gain observed during periods of locomotion (Batista-Brito et al., 2017, Mossner et al., 2020) weakening this explanation.

A final explanation could be that chronic VIP-IN ablation shifted inhibition away from the soma and toward distal dendritic sites. Of all INs, PV-INs provide the largest level of inhibition on pyramidal cells when controlling for cell population, unitary inhibitory postsynaptic charge, and probability of connection to pyramidal cells (Pfeffer et al., 2013). Given that chronic VIP-IN suppression is expected to lift inhibition off of SST-INs (Pfeffer et al., 2013; Pi et al., 2013; Fu et al., 2014; Karnani et al., 2016; Garcia-Junco-Clemente et al., 2017; Cone et al., 2019), more SST-INs would be allowed to inhibit PV-INs. As a result, pyramidal cells may experience less inhibition from PV-INs at the soma and more inhibition through distal dendritic sites from SST-INs. Given that action potentials are determined by the integration of all inhibitory and excitatory postsynaptic potentials at the cell soma, the shift in inhibition along the somatodendritic axis of pyramidal cells may make firing of pyramidal cells more likely. As a result, caspase mice could experience greater response gain to visual stimuli compared to control mice.

In summary, we find that localized ablation of VIP-INs in the primary visual cortex may improve the perceptual learning timeline of a contrast detection task and final steady-state performance during times of locomotion when using both full-screen and small vertical grating stimuli. VIP-IN ablation does not appear to affect performance during naivety. Given that the greatest change in performance occurred in the 1-10% contrast range, future experiments should aim to gain data granularity over that specific range. The clear role of VIP-INs in perception and perceptual learning highlighted in this paper reveals the need for future work to explore the robustness of our findings by altering the parameters of the behavioral task, including stimulus size.

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SUPPLAMENTAL MATERIALS

Supplemental Methods, Figure S1, and Figure S2 are available in the online appendix.

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ABSTRACT

The delay line is a fundamental circuit design component which slows down a signal with minimal attenuation to provide delay effects, with applications that include interferometry and signal filtering. Cryogenic superconducting delay lines can be less lossy than their regularly conducting counterparts. Scientists can engineer microwave photons with coherence times of several microseconds (\(\mu s\)), longer than current on-chip delays. We utilize the high dielectric constant (\(>10^4\)) of strontium titanate at cryogenic temperatures to slow down signal propagation on a coplanar waveguide. Here, we present a design for an on-chip 5 \(\mu s\) superconducting delay line at 5 GHz with small enough footprint to fit on-chip. This delay is more than 200 times longer than previously demonstrated while simultaneously more compact, enabling new regimes of interferometry. We also use simulations to characterize the sensitivity of the optimized design to alternative fabrication parameters. These designs may be useful for quantum information systems and integrated circuit design.

INTRODUCTION

Delay lines are one of the building blocks of circuit design whose function is to introduce a known delay between an input signal and an identical output signal with minimal loss. Using superconductivity in the design of the delay line is particularly attractive because such designs may render loss orders of magnitude lower than that of conventional delay lines. (Talisa et al., 1995) Superconducting delay lines have many potential applications, from electronic warfare and radar systems, (Kapolek et al., 1993; Liang, Shih, Withers, Cole, & Johansson, 1996) to signal storage and processing systems (Hattori, Yoshitake, & Tahara, 1999) and delay line filters. (Huang, 1997)

As with other delay lines, geometry and design are keys to the performance of superconducting delay lines. A review of superconducting delay line designs including microstrip, stripline, coplanar waveguide (CPW), and conductor-backed (grounded) CPW presents the state of the art in the field. (Su, Wang, Huang, & Lancaster, 2008) There are also different patterns for packing the line onto a wafer including double-spiral, meander line, unit-cell, and other compound designs. The goal of superconducting delay line design is to maximize the delay time on a given wafer area with minimal dispersion and loss. Secondary concerns include maintaining wide bandwidth of functionality. The results are given in centimeters of delay length and nanoseconds of delay time, ultimately rendering a figure of merit of propagation velocity. The longest recorded delay line is a 45 ns delay, achieved on a 4.3 m line—in other words, a propagation velocity of \(9.56 \times 10^7\) m/s or 0.319. (Hohenwarter, Track, Drake, & Patt, 1993) We propose and computationally verify a delay line design utilizing a high-dielectric medium to achieve a slowdown of more than 200 times with an even smaller footprint. This regime of superconducting delay approaches the limit of microwave photon decoherence time on the order of \(\mu s\). (Rigetti et al., 2012)

The key to this design is strontium titanate SrTiO\(_3\) (hereafter STO). STO is a crystal in the class of ferroelectric perovskites which demonstrate a quantum paraelectric phase transition wherein they develop a spontaneous electric polarization. For STO, this transition means that its dielectric constant goes from around 300 at room temperature to very large values in the tens of thousands below the critical temperature of 4 K. (Müller & Burkard, 1979) For the (001) orientation, it reaches a constant value of 11,000. (Sakudo & Unoki, 1971) Moreover, STO has a very small dielectric loss tangent on the order of 10\(^{-3}\) at small temperatures. (Krupka, Geyer, Kuhn, & Hinken, 1994) Lastly, the dielectric constant of STO is voltage tunable. This extra parameter, attributed to the presence
of oxygen vacancies, increases its functionality in embedded devices. (Davidovikj, Manca, van der Zant, Caviglia, & Steele, 2017) Altogether, these factors as well as the significant documentation of other research make STO an optimal choice compared to similar crystals, such as KTaO$_3$ (Krupka et al., 1994) Other high-dielectric constant and low-loss ferroelectric materials have previously been used in phase shifters using delay lines; however, prior investigations with STO have not cooled the STO below 20 K, thus limiting the potential of the characterization. (Jackson et al., 1992) STO has been used in electrically tunable filters (Findikoglu et al., 1996) and resonators, (Adam, Fuchs, & Schneider, 2002) and it may be suitable for future use in microwave domain EM probes.

**SrTiO$_3$ CHARACTERIZATION**

We began our process by experimentally verifying the quantum paraelectric phase transition of STO, which has been studied theoretically and experimentally for the past several decades. We coupled an STO crystal slab to a microwave resonator by placing the STO flush on top and measuring the resulting change in resonance. In particular, during this process we also sought to characterize the strength of the coupling dependent on the spacing between the STO and the microwave resonator. For our resonator, we used an ‘ouroboros’ resonator (Han, Zou, & Tang, 2016)—so named because of its resemblance to the Greek symbol of a snake eating its own tail—which is a simple LC resonator. The ourobos consisted of a “capacitor” formed by pairs of teeth surrounding another ring shunted by an “inductor” made of a long, arc-shaped narrow wire (Figure 1a, b). When the ourobos was excited on resonance $\omega_0$, the electric field response was strong and tightly confined to the capacitor rings (Figure 1c). The resonance frequency of the ourobos was determined using the finite element high-frequency simulation solver by ANSYS and experimentally verified using a vector network analyzer. We packaged the sample by suspending it

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**Figure 1.** (a) Ouroboros design with large inductive ring $R$ and small capacitive interlocking rings $r$. (b) Close-up of interlocking rings. (c) Electric field at resonance is confined to the capacitor of interlocking rings.

**Figure 2.** (a) The simulated ourobos geometry had a resonance at 9.43 GHz. (b) Experimental characterization agrees with resonance dip at 9.35 GHz. The difference may be attributed to coupling effects in the chamber.

1We used an ourobos with a double gap designed and fabricated by Wei Fu. It was made by electron-beam lithography etching. The structure is patterned using e-beam lithography patterning of superconducting NbN 40 nm thick on a sapphire wafer 0.5 mm thick.
on a sapphire holder chip in an air cavity within a copper box. The cavity is probed by a hoop antenna parallel to the capacitor. The sample was cooled below 4 K in liquid helium. The antenna was connected to the VNA, which scanned over the microwave frequencies from 20 MHz to 20 GHz. We measured the reflectance S11 to determine the resonances. On resonance, the locally confined electric field of the ouroboros sample would cause the signal reflectance to sharply dip. The LC resonant frequency is

$$\omega_0 = \frac{1}{\sqrt{LC}}.$$  \hfill (1)

Inserting a dielectric increases the capacitance by r, thereby decreasing the resonant frequency from its bare value by $1/\sqrt{r}$. For STO with dielectric constant 11,000, this would mean the resonant frequency would shrink more than 100-fold.

These calculations assume the STO is flush with the superconducting NbN. Due to the complexity of crystal lattice matching in epitaxial growth (see Discussion), the presence of an air gap between the STO wafer and NbN ouroboros printed directly onto sapphire substrate must be taken into consideration. We analyzed the reflection spectrum with either 167 or 500 μm of air gap or sapphire substrate spacing between the sample and resonator. The goal of these different configurations was to distinguish the cavity modes due to the finite nature of the packaging from the actual ouroboros resonance mode. We would be able to tell them apart if we had sufficient coupling between the antenna and the resonator in the presence of STO. We purchased a $5 \times 5 \times 0.5$ mm STO sample from MTI Corporation and probed it using input powers from -60 to 0 dBm to demonstrate the resonator’s nonlinear response at higher power (Figure 3). In the presence of STO, this nonlinearity shifts the resonator mode to lower resonant frequencies at higher power, whereas this behavior is the opposite for the cavity modes.

Ultimately, we were unable to definitively recreate the characterization of the specific dielectric value. There were many cavity modes which obfuscated the results since we could not methodically define the coupling of the antenna to the resonator with proper spacing due to different air gaps. Nevertheless, we were able to demonstrate that all the modes were substantially redshifted in the presence of STO. In Figure 3, the unconfirmed mode was shifted by over an order of magnitude due to the high dielectric environment. In addition, this investigation confirmed the very low attenuation of STO since even the cavity mode had a very high quality factor of nearly $10^3$, which is key for superconducting delay lines.

**SUPERCONDUCTING DELAY LINE DESIGN**

Having qualitatively confirmed the characteristics of the STO, we then proceeded to the design of the superconducting delay line. For our delay line, we chose to create a CPW superconducting delay line because it has low spurious modes, high integration level, and easy integration of parallel and series components. (Houdart, 1976) For
the CPW design, I used two different softwares: Sonnet Suites’ EM package and ANSYS HFSS. The former performs stacked 2D finite element analysis. This was not only faster, but also allowed for the input of direct kinetic inductance \( L_\text{K} \) for the superconducting NbN sheet. The latter calculated full 3D finite element solutions, though it was slow and required input of sheet reactance for the sheet \( R_\text{S} \) rather than kinetic inductance, so it was only valid for a single frequency value as \( R_\text{S} = 2\pi f L_\text{K} \).

The goal of our CPW line design, again, was to maximize the delay time by slowing down the propagation constant of the signal as much as possible. The propagation constant is

\[
\nu \propto \frac{1}{\sqrt{LC'}}
\]

(2)

\( L' \) and \( C' \) are the values for the effective impedance and capacitance of the line. The value for the propagation constant is reminiscent of the resonant frequency for the LC resonator, presented in Equation 1, though the phenomena are different since here we are dealing with a CPW line. We calculate the propagation constant by varying the length of the line by a small amount \( \Delta t \), leading to a global phase shift \( \Delta \phi \). We use the relation of these variables to calculate the characteristic wavelength of the line which would have the phase go through a full \( 2\pi \) rotation. We multiply this by the frequency, which for reference we take to be 5 GHz across simulations, to get the propagation constant.

\[
\nu = f \cdot \frac{2\pi \Delta \phi}{\Delta t}
\]

(3)

In addition to the propagation constant, we record the characteristic impedance to ensure that the delay line, when integrated with other circuit elements, does not suffer from an impedance mismatch. Though we can use impedance matching transformers to translate between different impedances, these will introduce more loss into the system on the order of several dB. Minimizing their use will deliver better results.

There are many parameters which go into CPW design: the dielectric constants \( \varepsilon_{r1} \) and \( \varepsilon_{r2} \) below and above the waveguide, corresponding substrate heights \( h_1 \) and \( h_2 \), CPW thickness \( t \), center patch width \( s \), the gap width \( w \), and air gap \( a \) (Figure 4). The below material is sapphire with dielectric constant 11 and thickness 0.5 mm, and the above material is STO with dielectric constant 11,000 and thickness 0.5 mm in our simulations. The thickness of the CPW was fixed to 40 nm and incorporated into the simulation by setting the kinetic inductance at 40 \( \text{pH/} \mu \text{m} \). Thus, our parameter space spanned the center patch width \( s \), gap width \( w \), and air gap \( a \) between the CPW and the above STO crystal.

RESULTS AND DISCUSSION

The optimal CPW delay line that we simulated has 1 \( \mu \text{m} \) center width, 1 \( \mu \text{m} \) gap width, and no air gap (in the ideal case that the CPW is printed directly onto STO). This CPW has a characteristic impedance of 18 \( \Omega \) and a propagation constant of \( 4.2 \times 10^7 \text{ m/s} \) or 0.0014\( \text{e} \) at 5 GHz. This signal propagation is more than 200 times slower than the best superconducting delay line value. If this design is integrated to create a 5 \( \mu \text{s} \) delay, then it would only require

![Figure 4. CPW design parameters.](image)

![Figure 5. The CPW is highly sensitive to the existence of the air gap. For any air gap, the propagation constant and characteristic impedance quickly increase. 5 \( \mu \text{m} \) center width and 5 \( \mu \text{m} \) gap width.](image)
2.1 m of line. If the line conservatively requires a 20 μm berth for proper in-plane grounding, then it would be able to fit onto 1 cm² chip with a meander pattern. This very small footprint allows for delay lines to be easily integrated on-chip into microwave systems.

The critical assumption is that there is no air gap. The effect of the high dielectric constant is only relevant if the electric fields of the CPW penetrate deep enough into the STO. However, air readily quenches the electric field, so the behavior of the system is very sensitive to the gap. The elimination of the air gap in practice would require the STO to be epitaxially grown directly on the superconducting resonator substrate. This is certainly possible but makes the fabrication process more difficult. The propagation constant and characteristic impedance quickly jump with any air gap, though once the air gap is opened, these values do not significantly vary (Figure 5). These values are much closer to the values when there was no STO present at all, for which the characteristic impedance is 248 Ω and the propagation constant is 0.045c.

With an air gap present, we further optimized the CPW with different center and gap widths (Figure 6). The propagation constant tends to decrease with a wider center patch. With a larger center width, the capacitance tends to increase because of the effective area of the CPW line. However, this increased width also decreases the kinetic inductance which is proportional to the cross-sectional area of the superconducting material, causing a nonlinear relationship (Figure 6a). The propagation constant does not vary significantly with the gap width (Figure 6b). We would expect that a wider gap would decrease the capacitance and hence increase the propagation constant. We do not see this effect, and it is likely that this is due to the bounds of the simulations’ precision or rounding errors in the extraction of the propagation constant, since the characteristic impedance does increase for wider gap widths as expected.

There are still other considerations which this investigation did not explore. We did not factor in attenuation into our simulations, instead assuming that everything was lossless. Dielectric attenuation in a CPW may be approximated as (Pozar, 2009)

\[ \alpha_f \approx 4.343 f_0 \varepsilon_{\text{eff}} \left( \frac{\varepsilon_r - 1}{\varepsilon_r + 1} \right) \tan \delta \]

in dB/m where \( \varepsilon_r \) is the dielectric constant of STO, \( \varepsilon_{\text{eff}} \) is the effective dielectric constant of the system, and \( \tan \delta \) is the loss tangent. The expression can be simplified considerably since STO has such a large dielectric constant and \( \varepsilon_{\text{eff}} \) may be estimated by \( \varepsilon_r/2 \). For a 5 GHz signal and with loss tangent of 10⁻³, the attenuation has an upper bound of 30 dB/m, which would effectively quash the signal. This would need to be confirmed in order to confirm the viability of STO in use for superconducting delay lines. However, by using a more lossless material such as KTaO₃ (Krupka et al., 1994) such that loss is less than 2 dB/m, the delay propagation constant may be sacrificed to preserve the signal. In addition, there would need to be further research about the effect that meandering has on the behavior of the line. These investigations were done exclusively with straight lines, meaning that there was no characterization of potential losses due to bends in the wire. Further analysis must be conducted to properly characterize the meandering such that there is no cross-coupling between bends. Lastly, one of the key features of STO is its dielectric voltage tunability. If this is experimentally realized, it may be particularly applicable for expanding the bandwidth of the active superconducting delay line. Elsewhere, this tunability has led to 10-20% variance in the dielectric constant, significantly widening the band for which the device may be usable. (Jackson et al., 1992)

![Figure 6. (a) Sensitivity to center width (reference: 5 μm gap, 1 μm air gap); and (b) sensitivity to gap width (reference: 5 μm center width, 1 μm air gap).](image-url)
CONCLUSION

In conclusion, we have presented a design for a coplanar waveguide superconducting delay line enhanced by strontium titanate which achieves a significant improvement in slowing down the propagation constant of microwave signals over previous literature results. STO, with its low loss tangent and extremely high dielectric constant value, may be well-suited for integration into superconducting delay lines. The functionality of this simple design with an STO half-space can be further extended in future research by taking advantage of the voltage tunability of the dielectric constant. The disruptive effect of an air gap means that the fabrication of this device will be complicated by the need for direct growth of STO on the delay line. Nevertheless, this design signals a new realm of research using high-k, low-loss materials which may have promising results. (Krupka et al., 1994) Delays on the order of microseconds can be exploited by experiments which approach the limit of microwave photons’ coherence, while the small footprint of this delay device would be useful for microwave filters and integrated microwave photonic design.

REFERENCES


**ABSTRACT**

Neurons are complex biological systems which develop intricate morphologies and whose dendrites are essential to receiving and integrating input signals from neighboring neurons. While much research has been done on the role of dendrites in neuronal development, a further understanding of dendrite dynamics can provide insight into neural development and the cellular basis of neurological diseases such as schizophrenia, Down’s syndrome, and autism. The Jonathon Howard lab hypothesizes that microtubules are a primary driving force in dendrite dynamics. Since it is known that microtubules display dynamic instability, rapidly transitioning between growth, paused, and shrinking states, the Howard lab proposes a similar 3-state transition model for dendrite dynamics. However, this model remains to be rigorously evaluated on dendrite branch data. In this paper, I develop a novel implementation of the Gibbs sampling algorithm for parameterization of the proposed 3-state mixture model, improving upon prior parameterization methods such as least squares fitting. Furthermore, I apply the algorithm on a confocal microscopy dataset of measured dendrite branch velocities from Class IV dendritic arbors in Drosophila melanogaster, demonstrating a good fit of the model to the data.

**INTRODUCTION**

1.1 Neuronal Dendrite Morphogenesis

Neurons are extraordinarily complex biological systems whose morphological structure and dynamics allow them to efficiently process signals and form the circuitry of the brain. Dendrites, which branch out of the neuron’s cell body, play a crucial role in receiving and integrating input signals from neighboring neurons. A neuron’s specific dendrite morphology and patterning plays an important role in determining which signals the neuron receives and how it processes them. Understanding dendrite morphology and dynamics—as well as the underlying mechanisms driving dendritic development—has important implications for elucidating neural and brain development and for enhancing our understanding of the cellular basis of neurological and neurodevelopmental disorders.

Over the past several decades, studies on *Drosophila melanogaster* neurons have revealed a broad range of genetic, molecular, and biophysical mechanisms contributing to dendrite morphogenesis. (Jan & Jan, 2010) In particular, it has been shown that microtubules play essential roles in dendrite growth, dynamics, and patterning. (Jan & Jan, 2010) As a result of these mechanisms, different neurons develop distinct dendrite morphologies including different dendrite sizes, branching patterns, and area coverage (dendritic field). These structural differences allow certain neurons to carry out distinct physiological functions within the neural circuitry of the brain. In particular, four distinct classes of dendritic arborization neurons have been identified in *D. melanogaster*: (Jan & Jan, 2010)

1.2 Modelling Dendrite Branch Dynamics

Since microtubules play important roles in dendrite dynamics (Jan & Jan, 2010), the Jonathon Howard lab hypothesizes that dendrites should display similar dynamic properties to microtubules. In particular, it is known that microtubules display dynamic instability, rapidly transitioning between growing, shrinking, and paused states on the order of minutes. (Conde & Cáceres, 2009) Such rapid transitions allow microtubules to efficiently adopt new spatial arrangements in response to cellular needs and changes in the environment. (Conde & Cáceres, 2009) It stands to reason that dendrites would take advantage of microtubule dynamic instability for dendrite branch development, attainment of particular dendrite morphologies and branching patterns, and rapid response to stimuli from neighboring neurons. The Howard lab thus hypothesizes that dendrite branches should display the same three dynamic branching states—growing, paused, and shrinking—that can be observed in microtubules.
Studies in the Howard lab have focused on dendrite dynamics and branching processes in Class IV dendritic arborization neurons of *D. melanogaster*. Using confocal microscopy, the Howard lab tracked the spatial and temporal dynamics of dendrite branch tips, recording a time series of branch lengths. Each time series consisted of a track of a single dendrite branch length for 30 minutes with 441 total tracks recorded. From this data, the corresponding dendrite branch velocities were computed. A histogram of the raw velocity data is shown below (Fig. 1).

![Figure 1. Raw dendrite branch velocity histogram.](image)

Building upon the 3-state hypothesis for dendrite dynamics, the Howard lab hypothesizes that dendrite branch velocities from Class IV dendrites in *D. melanogaster* can be segmented into distinct growing, paused, and shrinking state velocities. Furthermore, the velocities of each state can be represented according to a unique velocity distribution which can be modelled as a Gaussian for the paused state, log-Normal for the growing state, and negative log-Normal for the shrinking state. As such, the dendrite branch velocity data can be modelled as a three-state log-N-Gauss-log-N mixture model with unique mean, variance, and weight parameters (eq. 1).

\[
\begin{align*}
    \gamma_i & \sim w_1 \frac{1}{(y^+)\sigma_1\sqrt{2\pi}} \exp\left(\frac{-(\ln(y^*) - \mu_1)^2}{2\sigma_1^2}\right) + \\
    \gamma_i & \sim w_2 \frac{1}{\sqrt{2\pi}\sigma_2} \exp\left(\frac{-(y - \mu_2)^2}{2\sigma_2^2}\right) + \\
    \gamma_i & \sim w_3 \frac{1}{|y|\sigma_3\sqrt{2\pi}} \exp\left(\frac{-(\ln|y|) - \mu_3)^2}{2\sigma_3^2}\right)
\end{align*}
\]

where \(y^+\) refers to only positive velocity values in the dataset (for the log-Normal growth state) and \(y^-\) refers to only negative velocity values (for the negative log-Normal shrinking state).

1.3 Applying Bayesian Inference for Model Parameterization

In recent years, Bayesian inference has gained popularity for model parameterization. Through the application of Bayes rule, Bayesian inference allows for the calculation of posterior distributions for model parameters that can be updated with new data. Furthermore, in cases where models are too complex to analytically calculate posterior distributions, Markov Chain Monte Carlo (MCMC) methods have allowed for estimation of posterior distributions by iteratively sampling from them. One such MCMC method is Gibbs sampling, which will be discussed in detail below. In this paper, I develop a novel implementation of the Gibbs sampling algorithm in order to parameterize the proposed log-N-Gauss-log-N mixture model for class IV dendritic arbors using Gibbs sampling. Furthermore, using Gibbs sampling, I seek to develop a statistically rigorous method for segmenting dendrite branch data into the hypothesized growing, paused, or shrinking dynamic states. The results of this model parameterization will allow for the assessment of the 3-state hypothesis for dendritic development, providing further insight into the dynamics of dendrite morphogenesis.

BACKGROUND ON GIBBS SAMPLING

In this section I will introduce the generalized Gibbs sampling algorithm and its application towards Gaussian models, leading up to my specified implementation of the Gibbs sampling algorithm for parameterizing a log-N-Gauss-log-N mixture model.

2.1 Bayesian Inference

In many diverse fields, scientists often use statistical models to explain and better understand complex, noisy natural processes. The goal of such modelling is to derive a model that adequately explains experimentally measurable or observable data. In order to do so, researchers are often faced with the task of estimating model parameters from the data. This task is known as statistical inference. (Lambert, 2018)

While traditionally, least-squares fitting methods, frequentist-based inference, and maximum likelihood estimation (MLE) have been used to estimate model parameters, they are only capable of providing point estimates of parameter values. On the other hand, Bayesian inference provides a rigorous method for determining poste-
probability distributions of the parameter space. The basis of Bayesian inference is Bayes’ rule. If we have a hypothesized model with parameters $\theta$ and observed or measured data $D$, we are able to use Bayes’ rule to make the following inversion: $p(D|\theta) \rightarrow p(\theta|D)$, using the following equation (Lambert, 2018):

$$p(\theta|D) = \frac{p(D|\theta)p(\theta)}{p(D)} \quad (2)$$

where $p(D|\theta)$ is known as the likelihood, $p(\theta)$ is known as the prior, and $p(\theta|D)$ is known as the posterior. The likelihood represents the probability of generating a certain sample of data $D$, given that we know the model that generated our data and that our model’s parameters equal $\theta$. The prior represents an initial assumption about the distribution of our parameter space before seeing the data. The denominator on the right-hand side is known as the marginal likelihood and represents the probability of obtaining a certain set of data, assuming we have a defined likelihood and a prior. Finally, and most importantly, the posterior is the end goal of Bayesian inference and represents our updated distribution across the parameter space after seeing the data. (Lambert, 2018)

### 2.2 Gibbs Sampling Overview

While closed-form solutions of the posterior distributions for simple models can be obtained using Bayesian inference, more complex models with many parameters may have no such solutions. Thus, it may not be possible to obtain exact posteriors for the parameters of complex models. Nonetheless, posteriors can be estimated using dependent sampling methods referred to as Markov Chain Monte Carlo (MCMC). The idea of MCMC sampling is that the posterior can be sampled from and, given enough samples, an approximation to the true posterior can be obtained.

One type of MCMC algorithm is known as Gibbs sampling. Its premise rests on the assumption that, while it may not be possible to obtain a closed-form solution for the multi-parameter posterior, it may be possible to obtain closed-form posteriors for single model parameters conditioned on the other parameters (using the idea of conjugate priors, Appendix A). (Fridman, 2019; Hines, 2015; Lambert, 2018) Thus, each parameter, dependent on the other parameters and the data, can be sampled from individually. Sampling for multiple iterations and updating the parameter values across every iteration, the posterior for each parameter can be recreated, essentially returning a cross-section of each parameter dimension in the original multi-dimensional posterior. (Lambert, 2018)

#### 2.2.1 Generalized Gibbs Sampling Algorithm

As a generalized example of the Gibbs sampling procedure, we can imagine that we have a model with $N$ unknown parameters, $\theta = (\theta_1, \theta_2, ..., \theta_N)$ associated with a model that we’ve hypothesized for our data. We also assume that we have an observed dataset, $D$. Our goal is to estimate the $N$-dimensional posterior, $p(\theta_1, \theta_2, ..., \theta_N|D)$.

While we may be unable to obtain a closed-form solution for this posterior, we may instead be able to obtain closed-form solutions for the conditional posteriors of each of the parameters individually:

$$p(\theta_1|\theta_2, ..., \theta_N, D), p(\theta_2|\theta_1, \theta_3, ..., \theta_N, D), ..., p(\theta_N|\theta_1, ..., \theta_{N-1}, D)$$

We can then apply the Gibbs sampling algorithm to sample from each of the conditional posteriors and estimate the $N$-dimensional posterior according to Algorithm 1 below (6).

---

**Algorithm 1: Generalized Gibbs Sampling Algorithm**

1. Initialize at a random starting point $(\theta^*_1, \theta^*_2, ..., \theta^*_N)$
2. for $t$ in $i$ iterations do 
3. randomize the order of sampling from conditional posteriors 
4. sample each parameter using the most recently sampled parameter values, i.e. for an order of $(\theta_1, \theta_2, ..., \theta_N)$, update as:
   5. $\theta^*_1 \sim p(\theta^*_1|\theta^*_2, ..., \theta^*_N, D)$
   6. $\theta^*_2 \sim p(\theta^*_2|\theta^*_1, \theta^*_3, ..., \theta^*_N, D)$
   7. ... 
   8. $\theta^*_N \sim p(\theta^*_N|\theta^*_1, ..., \theta^*_{N-1}, D)$
5. append $(\theta^*_1, ..., \theta^*_N)$ to $[\theta_1\_vals, ..., \theta_N\_vals]$ 
9. end for 
10. return $[\theta_1\_vals, ..., \theta_N\_vals]$ 

---

#### 2.2.2 Gibbs Sampling Example for Simple Gaussian Model

As a specific application of the Gibbs sampling procedure, we will look at a Gaussian model with two unknown parameters, $\mu$ and $\sigma$. Assuming that our data is generated from a Gaussian distribution, $y \sim \frac{1}{\sqrt{2\pi\sigma}} \exp(-\frac{(y-\mu)^2}{2\sigma^2})$, our model has a Gaussian likelihood for $N$ samples. We seek to determine a 2-dimensional posterior, $p(\mu, \sigma|y)$. Using the idea of conjugate priors, we can determine the closed-form solutions for both the $\mu$ and $\sigma$ parameters conditioned on the other parameter and our data, as follows:

It has been shown that the following priors are conjugate to the Gaussian likelihood (Jordan, 2010):

$$\mu|\tau \sim N(\mu_0, \tau_0\tau), \quad \tau \sim \text{Gamma}(\alpha, \beta) \quad (3)$$

where $\tau = 1/\sigma^2$. The corresponding posteriors can then be
derived from the priors above (Jordan, 2010):

\[ r | y \sim \text{Gamma} \left( a + n/2, \beta + \frac{1}{2} \sum (y_i - \bar{y})^2 + \frac{mn_0}{2(n + n_0)} (\bar{y} - \mu_0)^2 \right) \]
\[ \mu | r, y \sim N \left( \frac{nt}{nt + n_0\tau} \bar{y} + \frac{n_0\tau}{nt + n_0\tau} \mu_0, \frac{nt + n_0\tau}{nt + n_0\tau} \right) \]  

(4)

We can thus determine the posterior \( p(\mu, \sigma | y) \) by using Gibbs sampling to iteratively sample from the \( \mu \) and \( \sigma \) conditional posteriors, respectively, and updating our parameter values, as described in algorithm 2 below:

**Algorithm 2**  
Gibbs Sampling Algorithm for Simple Gaussian Model  
1. Initialize as a random starting point \((\mu^0, \sigma^0)\)
2. for \( t \) in \( t \) iterations do
3. sample each parameter using the most recently sampled parameter values, update as:
4. \( r | y \sim \text{Gamma} \left( a + n/2, \beta + \frac{1}{2} \sum (y_i - \bar{y})^2 + \frac{mn_0}{2(n + n_0)} (\bar{y} - \mu_0)^2 \right) \)
5. \( \mu | r, y \sim N \left( \frac{nt}{nt + n_0\tau} \bar{y} + \frac{n_0\tau}{nt + n_0\tau} \mu_0, \frac{nt + n_0\tau}{nt + n_0\tau} \right) \)
6. append \((\mu^t, \sqrt{\frac{1}{t}})\) to \([\mu_{\text{vals}}, \sigma_{\text{vals}}]\)
7. end for
8. return \([\mu_{\text{vals}}, \sigma_{\text{vals}}]\)

**IMPLEMENTATION AND APPLICATION TO DENDRITE MORPHOGENESIS**

In this section I will describe the implementation of the Gibbs sampling algorithm for the 3-component log-N-Gauss-log-N mixture model used to model dendrite branch velocity distributions. I will first discuss the methods utilized in applying Gibbs sampling to mixture models, then discuss the specifics of my implementation.

### 3.1 Gibbs sampling for mixture models (6)

Mixture models contain multiple component distributions and thus require parameters to be sampled for each component in order to estimate the posterior. Accomplishing this involves a trick known as *data augmentation*, which adds a new latent indicator variable to the data that labels which component each data point was likely drawn from. For a k-component mixture model, we would have k potential categories for each indicator variable: \( cat \in \{1, 2, \ldots, k \} \). Additionally, we assume that in total our mixture model contains \((D + k)\) parameters representing \( D \) parameters from all the components of the model and \( k \) weight parameters associated with each of the \( k \) components. With the inclusion of latent variables, the posterior—originally with \((D + k)\) parameters—now contains \( N \) additional parameters indicating the category of each data point:

\[ p(\theta_1, \ldots, \theta_D, w_1, \ldots, w_k, cat_1, \ldots, cat_N | y) \]

These latent variables will be marginalized out in the process of Gibbs sampling, but are included to simplify the sampling procedure.

After including the latent indicator variables, the following conditional posteriors need to be computed in order to apply the Gibbs sampling procedure:

\[ p(\theta_1 | \ldots) \propto p(y | \ldots)p(\theta_1 | \ldots, p(\theta_N | \ldots) \propto p(y | \ldots)p(\theta_N) \]
\[ p(w_1 | \ldots) \propto p(y | \ldots)p(w_1 | \ldots, p(w_k | \ldots) \propto p(y | \ldots)p(w_k) \]
\[ p(cat_1 | \ldots) \propto p(y | \ldots)p(cat_1, \ldots, p(cat_N | \ldots) \propto p(y | \ldots)p(cat_N) \]  

(5)

This can be achieved by using the idea of conjugate priors (Appendix A) to find an appropriate prior to each of the likelihoods and obtain a closed-form conditional posterior for each parameter. Then, the conditional posteriors for each of the parameters can be sampled from and updated iteratively.

The posterior \( p(\theta_1 | \ldots) \) can be computed using the conjugate prior to the likelihood of whichever distribution our k-th component of the model comes from. For example, if one of our model components comes from an exponential distribution, we would use a Gamma prior and its corresponding posterior as shown in Appendix A. Likewise, if one of our model components comes from a Gaussian distribution, we would use a N - \( \Gamma^{-1} \) prior and its corresponding posterior as shown in section 2.2.1. The posterior for the k-th component, however, would be conditioned on the data assigned to the k-th component rather than the full dataset.

Next, in order to assign each data point to one of k components, we need to sample \( cat \) from k components with probability equal to the posterior probability of \( cat \) coming from each of k components, \( p(cat = 1 | \ldots), \ldots, p(cat = k | \ldots) \). This posterior probability can be expressed as follows:

\[ p(cat_i = j | \ldots) \propto p(y | cat_i = j, \ldots)p(cat_i = j) \]
\[ \propto p(y | cat_i = j, \ldots) * w_j \]  

(6)

As shown above, the posterior probability that data point \( i \) is assigned to category \( j \) is proportional to the likelihood of data point \( i \) being drawn from the j-th model component times the weight of the j-th component.

Each data point in the dataset is then assigned to one of k possible categories according to a categorical distribution with corresponding probabilities:
where, \( p(\text{cat}_i = 1 | ...) \), ..., \( p(\text{cat}_i = k | ...) \). The categorical distribution is an extension of the Bernoulli distribution to \( k \) dimensions and can be thought of as doing a \( k \)-dimensional coin flip with corresponding probabilities as the weights of each side of the \( k \)-dimensional coin.

The final parameters for which we need to determine a conditional posterior are the weight parameters \( w \) for each of the \( k \) model components. It’s important to realize that the weight \( w_j \) essentially represents the probability of sampling from the \( j \)-th component and thus—in order to ensure a valid probability distribution—the weights in the mixture model need to sum to one, \( w_1 + w_2 + + w_k = 1 \).

Using the conjugacy between a categorical likelihood and the Dirichlet prior, we can obtain a closed form for the joint posterior for all \( k \) weight parameters as follows:

\[
p(w_1, ..., w_k | ...) \propto L(\text{cat}|...) * p(w_1, ..., w_k) \\
\propto L(\text{cat}|...) * \text{Dir}(w_1, ..., w_k|\alpha_1, ..., \alpha_k) \\
= L(\text{cat}|...) * \prod_{j=1}^{k} \frac{\Gamma(\sum_{j=1}^{k} a_j)}{\Gamma(a_j)} \prod_{j=1}^{k} w_j^{a_j-1} \\
\propto \text{Dir}(w_1, ..., w_k | n(\text{cat}_1) + \alpha_1, ..., n(\text{cat}_k) + \alpha_k) \tag{8}
\]

where \( n(\text{cat}_j) \) represents the number of elements assigned to category \( j \).

With the steps above, we have derived the conditional posteriors for all of our model parameters and can now apply the Gibbs sampling algorithm to estimate the posterior of any mixture model whose likelihoods of its individual components have conjugate priors (i.e. for which \( p(\theta | ...) \) can be solved).

In the following section we will apply the steps shown in section 3.1 as well as the posterior for a Gaussian likelihood stated in section 2.2.2 to implement the Gibbs sampling algorithm for a 3-component log-N-Gaussian-log-N mixture model.

### 3.2 Gibbs Sampling for 3-component log-N-Gaussian-log-N Mixture Model

As stated in section 1.2, we hypothesize that dendrite branches display growing, paused, and shrinking states. As a result, dendrite branch velocity data can modelled as being distributed according to a 3-component log-N-Gaussian-log-N mixture model containing 9 mean, variance, and weight parameters that we seek to determine (eq. 1) (i.e. \( \mu_{\text{growth}}^{\text{growing}}, \mu_{\text{shrinking}}^{\text{shrinking}}; \sigma_{\text{growth}}^{\text{growing}}, \sigma_{\text{shrinking}}^{\text{shrinking}}; w_{\text{growth}}^{\text{growing}}, w_{\text{shrinking}}^{\text{shrinking}} \)).

### 3.2.1 Deriving Conditional Posterior Distributions

In this section I will derive the conditional posterior parameter distributions for the \( \mu \) and \( \sigma \) parameters of the 3-component log-N-Gaussian-log-N mixture model.

It is first important to note that any data distributed according to a log-Normal or negative log-Normal distribution can be transformed into a Gaussian distribution through a log transformation:

\[
y \sim \text{log-Normal}(\mu, \sigma^2) \rightarrow \ln(y) \sim N(\mu, \sigma^2) \\
y \sim \text{Negative log-Normal}(\mu, \sigma^2) \rightarrow \ln(|y|) \sim N(\mu, \sigma^2) \tag{9}
\]

Then, assuming the data is either generated from a Gaussian distribution or can be transformed to follow a Gaussian distribution with parameters \( \mu \) and \( \tau \), a Gaussian likelihood can be used for each component of the mixture model as follows:

\[
\ln(y_{\text{growing}} | \mu_{\text{growing}}, \tau_{\text{growing}}) \sim N(\mu_{\text{growing}}, \tau_{\text{growing}}) \\
\ln(y_{\text{shrinking}} | \mu_{\text{shrinking}}, \tau_{\text{shrinking}}) \sim N(\mu_{\text{shrinking}}, \tau_{\text{shrinking}}) \tag{10}
\]

where \( \tau = 1/\sigma^2 \). Given a Gaussian distributed dataset for each model component with unknown parameters \( \mu \) and \( \tau \) and their corresponding conditional posteriors (eq. 9), the \( N \cdot \Gamma^{-1} \) distribution can be sampled from to generate an approximation of the posterior parameter distributions according to algorithm 3:

#### Algorithm 3 Sampling from the \( N \cdot \Gamma^{-1} \) posterior

1. **Initialization:**
   1. \( \bar{\mu}_0 = \text{mean(dating)} \)
   2. \( n_0 = 2 \)
   3. \( \alpha = \text{length(dating)} \)
   4. \( \beta = \frac{1}{2} \sum (\text{data} - \mu_0)^2 \)
   5. \( A = \text{length(dating)} \)

2. **for** i in n_samples **do**
   1. \( \bar{\mu}^t = \alpha + A/2 \)
   2. \( \bar{\sigma}^t = \beta + 1/2 \sum (\text{data} - \text{mean(dating)})^2 + 1/2 \sum (\text{mean(dating)} - \mu_0)^2 \)
   3. \( \bar{\sigma}_{\text{posterior}} = \beta + 1/2 \sum (\text{data} - \bar{\mu})^2 \)
   4. **append** \( \sigma_{\text{posterior}} \) to \( \sigma_{\text{vals}} \) list

3. **μ** ~ \( N(\bar{\mu}, \sigma_{\text{posterior}}) \)
4. **σ** ~ \( \Gamma(\bar{\sigma}, 1/2) \)
5. **μ** ~ \( N(\bar{\mu}, \sigma_{\text{posterior}}) \)
6. **σ** ~ \( \Gamma(\bar{\sigma}, 1/2) \)
7. **return** \( \mu_{\text{vals}}, \sigma_{\text{vals}} \)
3.2.2 Defining the Gibbs Sampling Algorithm

The Gibbs sampling algorithm can be defined according to algorithms 3 and 4.

**Algorithm 4: Gibbs Sampling for log-N-Gauss-log-N Mixture Model**

```
1: for iteration t = 1, 2, ... N do 
2:   if t = 1 then 
3:     Use Otsu initialization, ... 
4:   Compute k1 and k2 thresholds to threshold 3 categories 
5:   Growing Set ← data > k2 
6:   Shrinking Set ← data < k1 
7:   Paused Set ← k1 < data < k2 
8:   else 
9:     Compute probabilities for growing, shrinking, or paused categories based on μ, σ, and w parameters sampled at iteration t - 1 
10:   p1 ← w*i_{growth} * log-N(data_set > 0, μ, σ) 
11:   p2 ← w*i_{paused} * log-N(data_set < 0, μ, σ) 
12:   p3 ← w*i_{shrinking} * log-N(0, μ, σ) 
13:   Fill p1 and p3 with zero's for p(data_set < 0) and p(data_set > 0), respectively 
14:   Assign each point in data_set as coming from growing, paused, or shrinking category with prob. p1, p2, p3, respectively 
15: for i in length(data_set) do 
16:   cat_i ~ Categorical(p1[i], p2[i], p3[i]) 
17: end for 
18: Reassign categories based on categorical samples, ... 
19: Growing Set ← data[cat_i == 1] 
20: Paused Set ← data[cat_i == 2] 
21: Shrinking Set ← data[cat_i == 3] 
22: end if 
23: Sample μ and σ parameter values according to normal-inverse-gamma posterior (*See Algorithm 3*) 
24: [μ*_{growth}, σ*_{growth}] ~ N^{-1}(log(Growing Set)) 
25: [μ*_{paused}, σ*_{paused}] ~ N^{-1}(Paused Set) 
26: [μ*_{shrinking}, σ*_{shrinking}] ~ N^{-1}(log(Shrinking Set)) 
27: Sample weight w parameter values according to Dirichlet posterior 
28: [w*i_{growth}, w*i_{paused}, w*i_{shrinking}] ~ Dirichlet(α1(Growing Set) + α2, Paused Set + α3, Shrinking Set + α3) 
29: *Repeat lines 8-28 for t = 2, ..., N 
30: end for 
```

RESULTS

In order to parameterize the dataset of dendrite branch velocities (Fig. 1) using the 3-component log-N-Gauss-log-N mixture model (eq. 1), the Gibbs sampling algorithm (Algorithms 3,4) was applied on both simulated and real datasets and the results are described below.

4.1 Effects of Gibbs Sampling Initialization on posterior predictions

In order to verify that the Gibbs sampling algorithm successfully converged to the true posteriors, we tested the algorithm’s performance on a simulated dataset with known parameter values. A dataset was simulated according to the 3-component log-N-Gauss-log-N mixture model with true μ, σ, and w parameters set to parameter values previously determined by the Howard lab using least-squares fitting for the dendrite branch velocity dataset (Fig. 3, Table 1).

The Gibbs sampling algorithm was initialized with random initialization, assigning each data point in the dataset to a growing, shrinking, or paused state with equal probability, with the restriction that only positive values could be assigned to a growing state and only negative values could be assigned to a shrinking state. Additional-

![Simulated Dataset Overlaid with True Distribution](image)

**Table 1**: Gibbs sampling parameterization for simulated model with known true parameters. Mean of Gibbs sampling estimated posteriors and 95% confidence intervals shown.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>True Parameter Value</th>
<th>Mean Gibbs Sampling Parameter Value</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ*_{growth}</td>
<td>0.3873</td>
<td>0.3956</td>
<td>(0.3814, 0.4098)</td>
</tr>
<tr>
<td>μ*_{paused}</td>
<td>0</td>
<td>Fixed at 0</td>
<td>N/A</td>
</tr>
<tr>
<td>μ*_{shrinking}</td>
<td>0.4369</td>
<td>0.4269</td>
<td>(0.4095, 0.4443)</td>
</tr>
<tr>
<td>σ*_{growth}</td>
<td>0.3624</td>
<td>0.3543</td>
<td>(0.3459, 0.3627)</td>
</tr>
<tr>
<td>σ*_{paused}</td>
<td>0.3387</td>
<td>0.3406</td>
<td>(0.3282, 0.353)</td>
</tr>
<tr>
<td>σ*_{shrinking}</td>
<td>0.3918</td>
<td>0.3940</td>
<td>(0.3828, 0.4052)</td>
</tr>
<tr>
<td>w*_{growth}</td>
<td>0.3351</td>
<td>0.3341</td>
<td>(0.3243, 0.3439)</td>
</tr>
<tr>
<td>w*_{paused}</td>
<td>0.3939</td>
<td>0.3916</td>
<td>(0.3803, 0.403)</td>
</tr>
<tr>
<td>w*_{shrinking}</td>
<td>0.271</td>
<td>0.2742</td>
<td>(0.2647, 0.2838)</td>
</tr>
</tbody>
</table>

**Figure 3**: A simulated dataset (blue histogram) of dendrite branch velocities according to a 3-component log-N-Gauss-log-N mixture Model (shown as orange distribution). True parameter values were set to values previously obtained by the Howard lab using least squares fitting to fit a log-N-Gauss-log-N mixture model to dendrite branch velocity data. True parameter values were set as: {true_μ*_{growth} = 0.3873, true_μ*_{paused} = 0, true_μ*_{shrinking} = 0.4369, true_σ*_{growth} = 0.3624, true_σ*_{paused} = 0.3387, true_σ*_{shrinking} = 0.3918, true_w*_{growth} = 0.3351, true_w*_{paused} = 0.3939, true_w*_{shrinking} = 0.271}
ly, since it is known that the mean velocity of the paused state is $0 \, \mu\text{m/min}$, the $\mu_{\text{paused}}$ parameter was fixed to 0. As shown in Figure 4, Gibbs sampling with random initialization failed to accurately recover the true parameters. Note that only the $\sigma$ posteriors are shown, but the algorithm failed to recover $\mu$ and $\omega$ posteriors as well.

Upon examination of the fitted distribution using the parameter means of the posteriors recovered by Gibbs sampling (Fig. 5), it is apparent that random initialization assigns many large negative and large positive values to the Gaussian paused state, causing difficulties for the algorithm to converge and causing it to falsely converge to a wide Gaussian (large $\sigma_{\text{paused}}$—not shown). Additionally, the algorithm converges to mean weights of about 0.91 for the Gaussian paused state and only about 0.046 and 0.042 for the log-Normal growing and shrinking states, respectively (posteriors not shown). Thus, it can be concluded that random initialization causes the algorithm to fit a wide Gaussian around the entire dataset, mostly disregarding the other components of the mixture model. This failure to converge to the true posterior may be attributed to the issue of multimodality in which the posterior contains multiple ‘modes’ of high probability parameter values and initialization far from the ‘true mode’ causes our sampler to converge to a lower probability mode.

To address the issue of multimodality, it stands to reason that initializing the sampler closer to the true posterior mode would facilitate proper convergence. In order to accomplish this, initializing the data segmentation from the mixture model into proposed growing, shrinking, and paused datasets such that the segmentation is closer to the true growing, shrinking, and paused datasets would aid in proper convergence of the sampler. Thus, a technique called Otsu’s method was employed to better initialize the categories of the data. Otsu’s method is used in image processing for image thresholding. The idea of Otsu’s method is to maximize the inter-class variance between any multi-class dataset. (Otsu, 1979) In our case, Otsu’s method was implemented to threshold our dataset into 3 categories that were used to initialize the proposed data segmentation in the Gibbs sampler (Algorithm 4, lines 2-7) (Fig. 6).

Running the Gibbs sampling algorithm for 1000 iterations using Otsu’s initialization successfully recovered the true parameters within 95% confidence intervals, as

---

**Figure 4.** MCMC chain and posterior for $\mu$ parameter using simulated dataset and random initialization. Red line represents true parameter value.

**Figure 5.** True model distribution (shown in blue) overlayed with the distribution obtained by Gibbs sampling (shown in orange). Parameter estimates were obtained by taking the mean of the posteriors obtained by Gibbs sampling.

**Figure 6.** Simulated dataset thresholded into 3 categories using Otsu’s method. Thresholds are $k_1 = -0.919$ and $k_2 = 0.714$
Taking the mean of each of the parameter’s posterior estimates from Gibbs sampling and plotting the fitted distribution, overlaid with the true distribution, shows that Gibbs sampling with Otsu initialization is successfully able to recover the true distribution and its parameters (Fig. 10, Table 1). In order to further assess the fit of the estimated distribution to the true distribution, the Kullback-Leibler (KL) divergence (Kullback & Leibler, 1951) was computed to be 0.0195, indicating an extremely good fit.

4.2 Parameterization of experimentally obtained dendrite branch velocity distribution

After successfully recovering the true parameters for the simulated model, I returned to my original goal of parameterizing the experimental dataset of neuronal dendrite branch velocities (Fig. 1). As stated previously, the Howard lab hypothesizes that dendrite branch velocity distributions follow a log-N-Gauss-log-N model with

---

**Figure 7.** MCMC chain and posterior for $\mu$ parameter using simulated dataset and Otsu initialization. Red line represents true parameter values. Green lines represent 99% confidence intervals. Confidence intervals and standard deviations shown in table.

**Figure 8.** MCMC chain and posterior for $\sigma$ parameter using simulated dataset and Otsu initialization. Red line represents true parameter values. Green lines represent 99% confidence intervals. Confidence intervals and standard deviations shown in table.

**Figure 9.** MCMC chain and posterior for $w$ parameter using simulated dataset and Otsu initialization. Red line represents true parameter values. Green lines represent 99% confidence intervals. Confidence intervals and standard deviations shown in table.

**Figure 10.** The true model distribution (shown in blue) overlayed with the distribution obtained by Gibbs sampling (shown in orange). Gibbs sampling with Otsu’s initialization successfully recovers the true distribution.
distinguishable growing, paused, and shrinking state velocities. The Gibbs sampling algorithm (Algorithm 4) with Otsu initialization can be applied to the experimentally-measured dataset after fixing $\mu_{\text{paused}}$ to 0. In order to increase confidence in posterior convergence, multiple MCMC chains were run. The posterior estimates for five MCMC chains with 95% confidence intervals are shown in Figures 11-13 and Table 2. In order to assess convergence of the Gibbs sampler, the Gelman-Rubin convergence diagnostic (Gelman & Rubin, 1992; Lambert, 2018) was used and produced $r_{\text{hat}}$ values below the threshold of 1.1, indicating that the MCMC chains had converged for all parameters (as shown in figures 11-13). Additionally, the effective sample size (Lambert, 2018) was computed for 1000 MCMC iterations (700 iterations after convergence) across five chains, producing effective sample sizes between 50 and 70 for all parameters (approximately 8-10% of the dependent sample size). The values are reported in Table 2.

Following assessment of posterior convergence, the means of each of the posterior parameter estimates were computed. The fitted distribution based on our mixture model (eq. 14) and estimated parameter values (Table 2) were plotted over a histogram of the dataset. In order to assess the fit of the estimated distribution to the distribution of the data, a non-parametric method for estimating a distribution known as the Kernel Density Estimate (KDE) was computed for the data and considered the target, or ‘true’ distribution. The KL divergence was then computed between the fitted distribution—with estimated parameters from Gibbs sampling—and the KDE distribution, resulting in a KL divergence of 0.2746 that indicated a good fit to the data (Fig. 14). Additionally, the

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean Parameter Value (across 5 chains)</th>
<th>95% Confidence Interval (for 1 chain)</th>
<th>Gelman-Rubin Convergence diagnostic ($r_{\text{hat}} &lt; 1.1$)</th>
<th>Effective Sample Size (dependent sample size = 700)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\text{growing}}$</td>
<td>0.2609</td>
<td>(0.2371, 0.2794)</td>
<td>1.0787</td>
<td>63.95</td>
</tr>
<tr>
<td>$\mu_{\text{paused}}$</td>
<td>Fixed at 0</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>$\sigma_{\text{growing}}$</td>
<td>0.2760</td>
<td>(0.2424, 0.3035)</td>
<td>1.0788</td>
<td>61.55</td>
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<tr>
<td>$\sigma_{\text{paused}}$</td>
<td>0.4936</td>
<td>(0.4823, 0.5075)</td>
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<td>69.81</td>
</tr>
<tr>
<td>$\omega_{\text{growing}}$</td>
<td>0.3816</td>
<td>(0.3632, 0.3951)</td>
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<td>52.01</td>
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<tr>
<td>$\omega_{\text{paused}}$</td>
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<td>68.66</td>
</tr>
<tr>
<td>$\omega_{\text{shrinking}}$</td>
<td>0.3039</td>
<td>(0.2953, 0.3148)</td>
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<td>67.34</td>
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<tr>
<td>$\omega_{\text{growing}}$</td>
<td>0.4600</td>
<td>(0.4414, 0.4741)</td>
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<td>55.67</td>
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<tr>
<td>$\omega_{\text{shrinking}}$</td>
<td>0.2361</td>
<td>(0.2279, 0.2466)</td>
<td>1.0822</td>
<td>64.47</td>
</tr>
</tbody>
</table>

Table 2: Gibbs sampling parameterization of Class IV dendrite branch velocity data. Mean parameter values for Gibbs sampling posterior estimates across 5 MCMC chains shown along with 95% confidence intervals. Gelman-Rubin diagnostic shown to assess MCMC chain convergence with a convergence threshold of 1.1. Effective sample size shown for all parameters.

Figure 11. MCMC chain and posterior for $\mu$ parameter using experimentally measured dendrite branch velocity dataset and Otsu initialization. MCMC chain was run for 2000 iterations. Red lines represent 99% confidence intervals. Confidence intervals and standard deviations shown in table.

Figure 12. MCMC chain and posterior for $\sigma$ parameter using experimentally measured dendrite branch velocity dataset and Otsu initialization. MCMC chain was run for 2000 iterations. Red lines represent 99% confidence intervals. Confidence intervals and standard deviations shown in table.
data segmentation into growing, paused, and shrinking states obtained by the Gibbs sampler is shown in Figure 15, indicating a clear segmentation of velocity data into distinguishable growing, paused, and shrinking states with the hypothesized log-N (for growing), Gaussian (for paused), and negative log-N (for shrinking) velocity distributions.

CONCLUSION

The results indicate that the Gibbs sampling algorithm can successfully be applied to parameterize mixture models of dendrite branch velocities. However, it is important to note that initialization appears to play an important role in the success of the Gibbs sampler for this case. Using Otsu’s method initializes the sampler closer to the true posteriors, allowing the sampler to successfully converge to the true posterior. Further investigation into initialization and the shortcomings of Gibbs sampling algorithms for mixture models and multimodal posteriors may be necessary.

The good fit of our distribution to the data (Fig. 14) and

Figure 13. MCMC chain and posterior for w parameter using experimentally measured dendrite branch velocity dataset and Otsu initialization. MCMC chain was run for 2000 iterations. Red lines represent 99% confidence intervals. Confidence intervals and standard deviations shown in table.

the reasonable segmentation (Fig. 15) further indicates that our choice of a three-component log-N-Gauss-log-N mixture model accurately models the data. This supports the Howard lab’s hypothesis that neuronal Class IV dendrites do indeed display distinguishable growing, paused, and shrinking states that can be observed in microtubules, supporting the hypothesis that dendrite dynamics are driven by microtubule dynamic instability. These results may provide further insight into the underlying biological mechanisms behind dendrite morphogenesis.

The results also provide a more rigorous means of quantifying model parameters with interpretable confidence intervals, as well as a rigorous method for segmenting experimental data into proposed states with an associated probability. This can improve methods for modelling and simulating dendrite morphogenesis, enhancing our

Figure 14. The dendrite branch velocity histogram (shown in blue) overlayed with the distribution obtained by Gibbs sampling (shown in orange). Gibbs sampling with Otsu’s initialization recovers parameters that result in a good fit to the data.

Figure 15. Results of final Gibbs sampling data segmentation into growing, paused, and shrinking states.
mechanistic and systems-level understanding of neural development. Furthermore, future studies may reveal differences in model parameters between wild-type, or ‘healthy’, neurons and mutant, or ‘diseased-state’, neurons, which may be used to explain observable differences in dendrite branching patterns, providing a dendrite morphology-based explanation for the emergence of neurological disease.

Since healthy cognitive functioning and certain neurological diseases have been linked to dendrite development, the results of this study and future studies on mutant dendrites may, in the long-term, help provide more insight into the importance of dendrite dynamics in proper neural development and how deviations in dendrite dynamics may contribute to the emergence of neurological disease.

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REFERENCES


APPENDIX A

Conjugate Priors

In certain cases, an exact closed-form solution for the posterior can be calculated without having to calculate the marginal posterior by selecting a mathematically convenient prior. More specifically, if a prior is chosen from a specified family of distributions such that the posterior will fall into the same family of distributions, it may be possible to obtain a closed-form solution for the posterior. These ‘mathematically convenient’ priors are known as conjugate priors. (Conde & Cáceres, 2009)

In order to explain how conjugate priors work, it is easiest to use an example. Thus, I will use a biophysically relevant example relating to ion channel patch-clamp recordings in order to demonstrate the use of conjugate priors. (Fridman, 2019; Hines, 2015)

Example: Ion Channel Patch-Clamp Recording (Fridman, 2019; Hines, 2015; Lambert, 2018)

Most cells, including neurons, contain proteins called ion channels on their membranes which allow for ions to flow between the interior and exterior of the cell. These ion channels regulate the concentration of ions across the membrane by stochastically transitioning between open and closed states according to a Poisson process. The time an ion channel spends in any given state (dwell-time) is known to follow an exponential distribution. An experiment can be carried out which tracks the time spent in each state and a histogram of dwell-times can be plotted, a simulation of which is shown in Fig. 2.

We first model the dwell-times as random variables from an exponential distribution, \( y_i \sim \lambda e^{-\lambda y_i} \). For \( N \) samples, we thus form an exponential likelihood:

\[
\prod_{i=1}^{N} \lambda e^{-\lambda y_i}
\]

Next, we seek to determine the time-scale parameter \( \lambda \) of our model based on our data. We can formulate this
problem in terms of Bayesian inference as follows:

\[ p(\lambda|y) \propto \prod_{i=1}^{N} \lambda e^{-\lambda y_i} p(\lambda) \]

Our goal is to select an appropriate prior, \( p(\lambda) \), such that we can obtain a closed form posterior for the time-scale parameter, \( p(\lambda|y) \). The conjugate prior to an exponential likelihood is the Gamma distribution:

\[ p(\lambda) \sim \text{Gamma}(\lambda|\alpha, \beta) = \frac{\beta^\alpha}{\Gamma(\alpha)} \lambda^{\alpha-1} e^{-\lambda \beta} \]

With the following set of steps we can see how the Gamma prior conveniently combines with the exponential likelihood:

\[ p(\lambda|y) \propto \prod_{i=1}^{N} \lambda e^{-\lambda y_i} \times \frac{\beta^\alpha}{\Gamma(\alpha)} \lambda^{\alpha-1} e^{-\lambda \beta} \]

\[ \propto (\lambda^N e^{-\lambda \sum_{i=1}^{N} y_i}) \times \left( \frac{\beta^\alpha}{\Gamma(\alpha)} \lambda^{\alpha-1} e^{-\lambda \beta} \right) \]

\[ \propto (\lambda^N e^{-\lambda \sum_{i=1}^{N} y_i}) (\lambda^{\alpha-1} e^{-\lambda \beta}) \]

\[ = \lambda^{\alpha+N-1} e^{-\lambda (\sum_{i=1}^{N} y_i + \beta)} \]

We observe that the simplified solution above follows the same form as the Gamma distribution, but with new hyperparameters, updated according to our data. Thus, we obtain the final closed-form solution for our posterior:

\[ p(\lambda|y) \sim \Gamma(\lambda|\alpha', \beta') \text{ s.t. } \alpha' = \alpha + N \text{ and } \beta' = \sum_{i=1}^{N} y_i + \beta \]

Using the idea of conjugate priors, we are able to solve for the posterior distribution of the time-scale parameter.
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