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# Quantifying Interdisciplinarity in Cognitive Science and Beyond

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## Abstract

Recent publications have lamented the dominance of psychology in cognitive science. However, this relies on a limited definition of collaboration between fields. We call for a renewed conception of interdisciplinarity as a “mixture of expertise.” We describe an information-theoretic measure of interdisciplinarity and apply it to multiauthored published articles. Results suggest that cognitive science journals mix expertise more than topically related journals. We suggest that perceptions of diminishing interdisciplinarity may in part be due to the emergence of different theoretical perspectives and use a semantic model to illustrate this argument. We conclude by describing some benefits of this broader conception.

*Keywords:* Interdisciplinarity; Cognitive science; Semantic modeling; Jensen–Shannon divergence

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## 1. Introduction

Recent commentaries on the current state of cognitive science contend that it has not lived up to its interdisciplinary definition. In particular, there is concern with the growing

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preponderance of psychology departments among author affiliations on cognitive science publications (Gentner, 2010; Núñez et al., 2019). Núñez et al. (2019) offer a rather grim assessment of the disciplinary composition of cognitive science: “Bibliometrically, the field has been largely subsumed by (cognitive) psychology, and educationally, it exhibits a striking lack of curricular consensus, raising questions about the future of the cognitive science enterprise.” (p. 782)

Both Gentner (2010) and Núñez et al. (2019) use departmental affiliation as the proxy for disciplinary composition of cognitive science, gathered from authorship in journal articles. Affiliations are telling. However, using departments as the *sole* metric for interdisciplinarity offers an incomplete picture. Indeed, the notion of “discipline” is often in flux from decade to decade, as scientists in various fields tend to do work that crosses traditional boundaries.

Moreover, departmental affiliations and structure are subject to pressures that go beyond disciplinary dynamics, such as bureaucratic or budgetary concerns. Because there are still relatively few cognitive science departments, many cognitive scientists work in single-discipline departments, such as psychology, linguistics, or computer science. This departmental structure often responds to historical, political, and economic trends (see, e.g., Wallerstein, 1996), which makes it difficult to map it directly onto the knowledge produced by a particular field. Finally, on a more historical note, the rise of cognitive science as a field has coincided with sweeping changes in the organizational culture of universities that have limited the control of academics over university management and fostered internal and external competition (Olssen & Peters, 2005). This has often made it difficult for new fields to institutionalize into, for example, their own departments or graduate programs (for a conceptual and anecdotal overview, see Sahlin, 2009; for a case study, see Ryan & Neumann, 2013).

Given these difficulties in judging interdisciplinarity through departmental affiliation, in this commentary, we discuss an alternative approach to assessing interdisciplinarity in teams, referring to this composition as *mixtures*. Importantly, this term is more general than evaluating disciplinary composition as the sole metric. Mixtures can come in various forms. Mixtures may be created by combining team members who have distinct histories, skillsets, or sharply distinct theoretical perspectives. “Interdisciplinarity,” under this formulation, has two defining parts. First, it is a mixing of disparate intellectual elements; second, it is a mixture suited to solving a specific scientific problem. This definition of interdisciplinarity encourages different approaches to quantifying mixtures in teams using bibliometric tools. In the next two sections, we offer examples of these metrics.

## 2. Measuring the interdisciplinarity of cognitive science

Analysis by Bergmann, Dale, Sattari, Heit, and Bhat (2017; see also Bhat et al., 2015) serves as an illustration of this bibliometric approach. Their research focuses not on departmental affiliation as a measure of interdisciplinarity, but instead on the publication history of coauthors on papers. The reasoning for such a metric is that departments are coarse-grained entities, and they may obscure diversity present in collaborations even within one department. For example, fruitful mixtures may be found between clinical and cognitive psychologists,

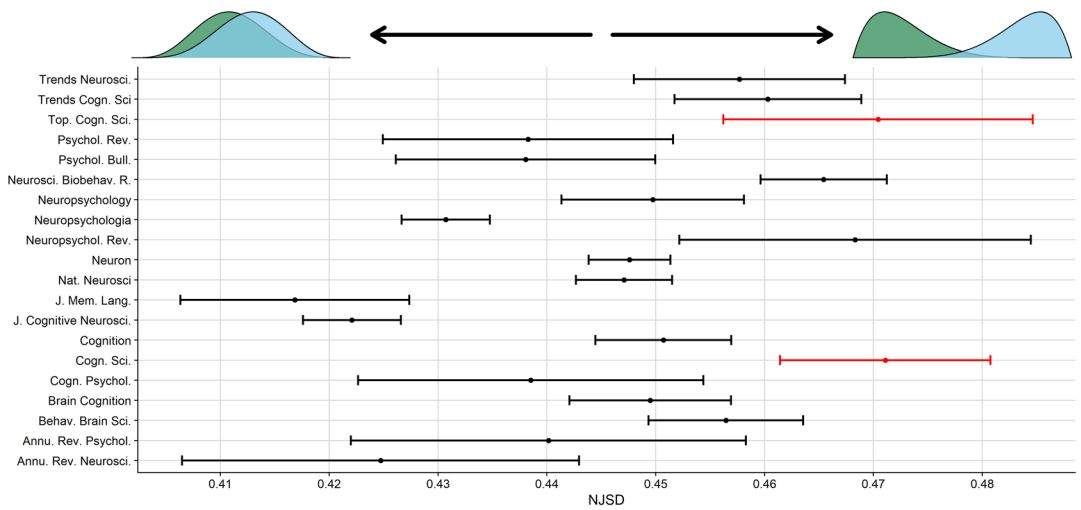


Fig. 1. Mean JSD of articles per journal along with 95% confidence interval when controlling for Gini and log total number of publications of all coauthors (NJSD). Estimates and confidence intervals were obtained using emmeans (Lenth, 2021). The journals of the Cognitive Science Society (indicated in red) are comparatively high on this score. To facilitate interpretation of the metric, two hypothetical cases are shown above illustrating the overlap of publication distributions at each extreme of the scale.

between two anthropologists trained in very different theoretical traditions, or even between a cognitive psychologist and a computational modeler that happen to work in a linguistics department.

Publication history provides a quantifiable index capturing important aspects of an author's work and focus. Bergmann et al. (2017) used Jensen–Shannon divergence (JSD) (Lin, 1991) as an information-theoretic measure of the diversity of publication histories, with high JSD reflecting an “interdisciplinary” collaboration in that two or more authors with distinct histories have chosen to work together. Such metrics offer new bibliometric analysis of team composition and success. Indeed, this JSD metric for interdisciplinarity may be a predictor of the impact of research (Bhat et al., 2015).

We followed up on the analysis of Bergmann et al. (2017) to examine recent JSD scores for *Topics in Cognitive Science* and *Cognitive Science* and compare them to 18 other journals, chosen because they are topically related to cognitive science, psychology, and neuroscience (Fig. 1). We used a sample from the Thomson Reuters Web of Knowledge (WOK) API<sup>1</sup> to collect publications from 2005 to 2018 in a manner consistent with Bhat and colleagues (2015) and Bergmann et al. (2017). Extensive methodological details are found in the Supplementary Materials, including links to code and data. We measured the collaborative network of the 23,519 articles from these 20 core journals, encompassing 45,046 unique coauthors and their publication history. For each article, a JSD score is obtained, permitting the calculation of average JSD scores per journal. Results are shown in Fig. 1.

Both *TopiCS* (estimated marginal mean (EMM, Lenth, 2021): 0.47, 95% CI: [0.456, 0.485]) and *Cogn. Sci.* (EMM: 0.471, 95% CI: [0.461, 0.481]), along with other cog-

nitive science journals, such as *TiCS* (EMM: 0.46, 95% CI: [0.452, 0.469]) and to a lesser degree *Cognition* (EMM: 0.451, 95% CI: [0.444, 0.457]), are among the journals with the highest JSD in the dataset. This suggests that, by this measure based on author publication history, these outlets spur collaborations that mix researchers with comparatively more varied expertise than the journals from psychology, the field taken to be subsuming cognitive science. Surprisingly, journals like *Neuropsychological Review* (EMM: 0.468, 95% CI: [0.452, 0.484]), *Trends in Neuroscience* (EMM: 0.458, 95% CI: [0.448, 0.467]), and *Neuroscience and Biobehavioral Reviews* (EMM: 0.465, 95% CI: [0.46, 0.471]), which would be expected to be low in interdisciplinarity, are also relatively high on this score.

We take the present analysis as an illustration that interdisciplinarity can go beyond departmental affiliation. For example, the latter relatively higher scores could be due to the interdisciplinarity inherent in the first two subfields of cognitive psychology and neuropsychology, founded to combine different methodological perspectives on the study of behavior. They are also both review journals, which could attract both a broader audience and a broader coauthorship.

We can also analyze these data by year to examine whether they fit to the more pessimistic view on the trajectory of cognitive science and its subsumption into psychology. For this, we divided our journals into three “topical” groups: cognitive science, psychology, and neuroscience. Then, we built a simple model of the evolution of JSD scores over the years in our database. First, the observed trend shows that mixture of expertise, as measured by JSD, is rising across the board in all three topical fields (over and above the effect of covariates, see Supplementary Materials). This is consistent with Wuchty, Jones, and Uzzi (2007) observation of the increasing proportion of scientific work performed by teams as opposed to individual authors. As we attempt to (linearly) control for the effect of the number of authors on JSD (see Supplementary Materials), an across the board increase of team collaboration *among peers*, and not only between mentors and junior researchers, could explain why all three of the assessed topical groups show an upward trend.

Another trend in Fig. 2 is that cognitive science journals are significantly more interdisciplinary than “pure” psychology journals across all the years of our dataset (pairwise comparisons between cognitive science and psychology journals for every year except 2009 ( $t(22, 371) = 2.161$ ) have  $p < .05$ , with  $t(22, 371)$  ranging from 2.876 in 2010 to 6.384 in 2014, Bonferroni adjusted for all 30 possible contrasts). Moreover, except for 2018 ( $p > .05$ ,  $t(22, 371) = 2.116$ ), cognitive science journals have a significantly higher mean JSD than neuroscience journals. There are no significant differences in the covariate-controlled linear slope between cognitive science and either psychology (difference: .00176,  $t(22, 371) = 1.447$ ,  $p > .05$ ) or neuroscience (difference:  $-.0011$ ,  $t(22, 371) = -1.413$ ,  $p > .05$ ). As a complement to this analysis, Fig. 2b shows the EMM for each journal in the database in each year between 2009 and 2018, with the journals of the Cognitive Science Society, *Cognitive Science* and *TopiCS*, marked in red. It can clearly be seen that both are above the median EMM JSD in every year.

Although primarily illustrative, these analyses suggest that the pessimistic view of the relationship between cognitive science and psychology is not warranted. Indeed, cognitive science seems to reliably bring together more divergent mixtures of expertise than psychol-

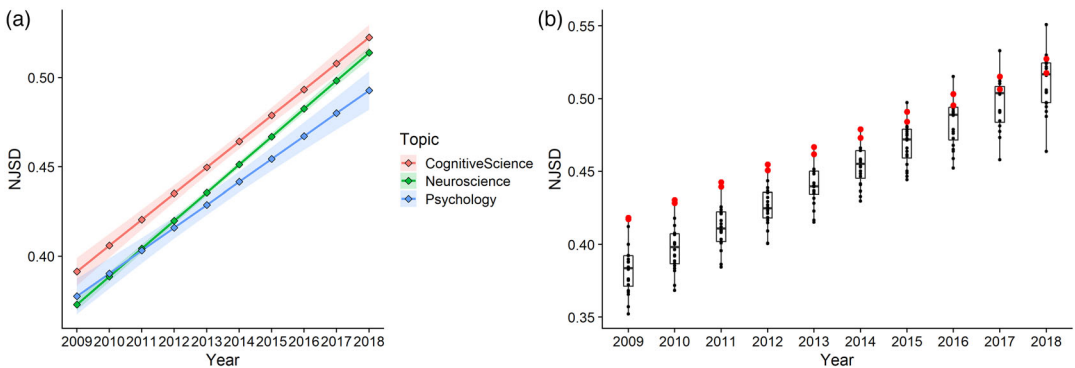


Fig. 2. (a) Predicted mean JSD across years for cognitive science, neuroscience, and psychology journals. The shaded areas mark 95% confidence intervals around the estimated mean. (b) Predicted mean JSD for each journal across year. *TopiCS* and *Cognitive Science* are marked in red. Points are overlaid over a boxplot marking the quartiles of the 20 predicted means for each year. In both plots, the included covariates are Gini coefficient, number of authors, and number of publications (see Supplementary Materials).

ogy and neuroscience journals. Moreover, in contrast to the claims made on the basis of departmental affiliation, this difference does not appear to be disappearing. Therefore, outlet-based JSD suggests that the field of cognitive science is manifesting a form of interdisciplinarity that enables novel mixtures of knowledge. This goes beyond the particular, historically contingent names of the departments that employ the researchers working in them.

### 3. Theoretical divergence in cognitive science

A bibliometric approach may also be valuable for developing new metrics quantifying methodological and theoretical mixtures. The proliferation of different perspectives (noted in Núñez et al., 2019) may be associated with different patterns of word use (Contreras Kallens & Dale, 2018). Such disparate terminology highlights distinct, emerging theoretical frameworks. These frameworks reimagine our field's traditional problems, introduce new methodologies and often challenge core conceptual assumptions of cognitive science (e.g., Anderson, 2003; Goldinger, Papesh, Barnhart, Hansen, & Hout, 2016; Newen, De Bruin, & Gallagher, 2018; Shapiro, 2019; Wilson & Foglia, 2021). But these terms may also be used to assess mixtures of expertise, as authors who adopt distinctive methods or theories may fruitfully collaborate in innovative ways.

These bibliometric measures can be devised using tools from cognitive science itself, like latent semantic analysis (LSA; Landauer, Foltz, & Laham, 1998; cf. Leydesdorff & Welbers, 2011). LSA can reduce a large batch of text (like abstracts) to obtain a set of vectors that captures the patterns of co-occurrences of different words. This space is often referred to as a “semantic space,” and can be explored for conceptual relationships. Using various metrics, such as the cosine of the angle between two-word vectors, two or more words can be assessed for their semantic similarity.

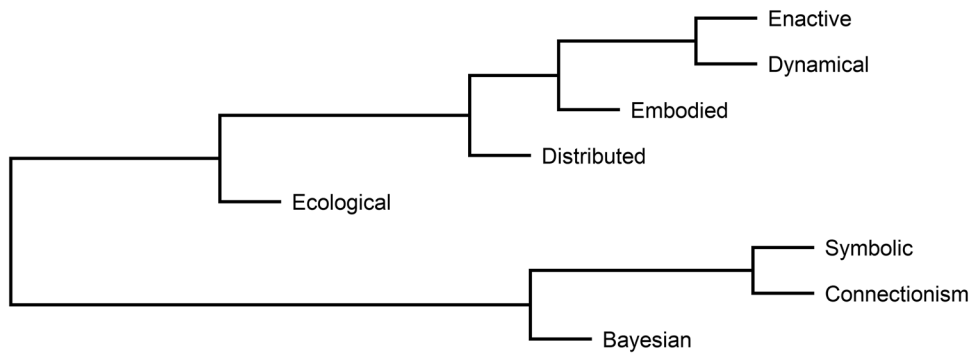


Fig. 3. Results of a hierarchical cluster analysis using a pairwise cosine distance matrix of the document loadings using the 100 first dimensions resulting from our LSA model. Clustering was determined with Ward's method for linkage and represented as a dendrogram. Contreras Kallens and Dale (2018) showed that this structure is relatively robust to the choice of dimensionality and can also be observed through patterns in document classification.

LSA, and more recent semantic modeling techniques, such as LDA (Griffiths & Steyvers, 2004) and word2vec (Mikolov, Sutskever, Chen, Corrado, & Dean, 2013), may help to map out the content of a field or to categorize journals according to their semantic characteristics. Contreras Kallens and Dale (2018) used a language-based model to build a sort of “semantic landscape” of the theoretical perspectives of cognitive science based on this underlying idea. They built an LSA model from word usage in abstracts for research articles that espoused one or more influential theories in cognitive science: *Bayesian*, *connectionist*, *enactivism*, *distributed cognition*, and so on. They found that LSA's semantic dimensions are structured in an intuitive and stable way, and that the semantic model can predict the theoretical perspective adopted in an article.

As an illustration, we extended this prediction methodology to the articles in the dataset collected for the prior analysis. Because the original models were built using articles from the domain of cognitive science, we only applied the models to abstracts from a subset of the journals here. We set a simple criterion that at least 1% (10) of the articles from the original training set of Contreras Kallens and Dale (2018) study had to be present in a journal here for inclusion. By that definition, these journals were included: *Behavioral and Brain Sciences*, *Cognition*, *Cognitive Psychology*, *Cognitive Science*, *Journal of Memory and Language*, *Psychological Review*, *TopiCS*, and *Trends in Cognitive Science*. We built a new term-by-document matrix of these articles, then integrated these new data with the LSA space of Contreras Kallens and Dale (2018), using methods described in Berry, Dumais, and O'Brien (1995). This resulted in a new representation of the articles from the journals, with each article corresponding to a vector projected into an LSA space. This quantitative content-based model offers fresh variation through which mixtures can be assessed, as there is quite a divergence in the parts of the semantic space that each of the journals carves out.<sup>2</sup>

Fig. 3 shows the results of a hierarchical cluster analysis on the similarity matrix of the articles we used to train our predictive models, that is, the original semantic space built in Contreras Kallens and Dale (2018). The dendrogram shows that the divergences are

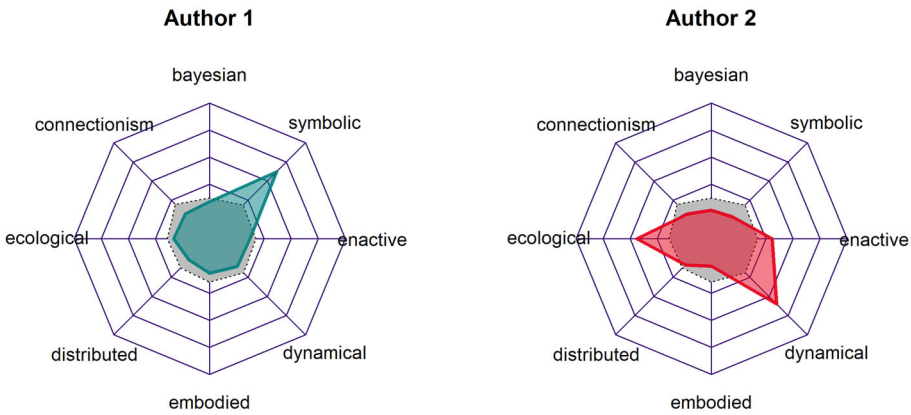


Fig. 4. Illustration applying a semantic model to two potential collaborators whose prior work is predicted to involve disparate methods or theories. Using the semantic model described here, a quantification of interdisciplinarity of a “mixture” of intellectual training may present fruitful opportunities, including perhaps data mining potential collaborators. Extensive description of this analysis is found in Supplementary Materials, including plots of journals and hundreds of authors who have published in the journals of the society.

structured into “camps,” with more “computational” (*Symbolic*, *Connectionism*, and *Bayesian*) approaches on one side and more “alternative” (*Embodied*, *Dynamical*, *Enactive*, *Distributed*, and *Ecological*) approaches on the other side. This illustrates the structured semantic space underlying articles from the new dataset here.

With these vectors, we used the statistical models trained on the original semantic space from Contreras Kallens and Dale (2018) to assign each article a score based on the probability of its theoretical orientation. Both authors and journals may be described in this way. A hypothetical illustration is offered in Fig. 4 (with detailed example figures and analyses to be found in the Supplementary Materials). Here, we conceptualize content overlap and nonoverlap as a further reflection of novel mixtures.

A semantic modeling approach in general may offer several novel approaches to measuring mixtures using the content of scientific publications. It can be applied across the many layers of academic and scientific activity—from journals to articles to individual authors—making new measures of mixture extensible. It is also possible to apply this measure of theoretical composition in a historical analysis, showing how journals have changed in their mixtures of theories (see Cohen Priva & Austerweil, 2015). The LSA model here focuses on theoretical composition, but one could imagine a similar analysis based on words that convey methodologies or other forms of expertise (e.g., Cooper, 2019). These preliminary results again illustrate that measures of mixture can go beyond formal disciplinary composition and institutional affiliation.

#### 4. Rethinking interdisciplinarity for a changing science

We have argued that departmental affiliation offers only a first diagnosis of intellectual history, theoretical approach, or specific methodology. Going beyond this approach, new

bibliometric measures may help to identify how mixtures of expertise can take different forms and help to advance an updated conception of “interdisciplinarity” that goes beyond the dusty confines of centuries-old disciplinary fiat.

In the first part of this commentary, we described an alternative measure of interdisciplinarity and explored how the journals *TopiCS* and *Cogn. Sci.* fare under one of them. The JSD measure does suggest that team compositions in cognitive science articles, on average, score highly among other psychology and neuroscience journals. This measure does not rely on assumed disciplinary or institutional composition. Much as early cognitive scientists did not want to see the confines of single disciplines as staking a claim on the mind, we should not take administrative cross-over as the sole bearer of this tradition in its modern form. Bibliometric analysis helps capture some of the variance underneath these coarse administrative groupings.

These measures by themselves are unlikely to alleviate the concern about cognitive science authorship patterns (Gentner, 2010; Núñez et al., 2019). However, we believe that the predominance of psychology affiliations might have an alternative, less dire explanation: As a discipline, psychology has a rather central interest in questions of the mind relative to all other fields of cognitive science. The study of “mind, brain, and behavior,” key to cognitive science’s definition is, of course, central to virtually *all* of psychology itself (see also Cooper, 2019, p. 872). Thus, cognitive psychology graduate programs may attract students from other disciplines who seek a community of peers and faculty studying the mind, and an amicable institutional setting in which to work. The coauthors of the present commentary, for example, converged on psychology from distinct histories themselves. We took our undergraduate training in philosophy, linguistics, and sociology, respectively. The intuition behind our quantitative approach is that being in a psychology department does not negate diverse expertise and intellectual history.

In a response to commentaries, Núñez et al. (2020) evaluate the state of the field in part through the lens of Gardner’s formal hexagon proposal and the different kinds of integration (Gardner, 1987). Gardner’s hexagon, wherein cognitive science is a (perhaps balanced) combination of philosophy, psychology, artificial intelligence, neuroscience, anthropology, and linguistics, was once our ideal image of the field. It may be timely, with data and tools at our disposal, to seek different notions of interdisciplinarity according to the evolving character of the research of cognitive science and the institutional realities of higher education administration. Whether cognitive science fits a rational reconstruction of some presupposed ideal cannot take precedence over its tendency to unite researchers from varied traditions to further our understanding of the mind. This is surely the spirit, if not the letter, of the cognitive science hexagon (Gardner, 1987).

In the second half of the commentary, we illustrated a word-based semantic model to quantify the distribution of theoretical perspectives in cognitive science. Apart from providing a novel view of the discipline, semantic models of theoretical perspectives provide new ways of addressing the controversies about cognitive science as a “degenerative discipline.” Earlier descriptions of cognitive science as in Gardner (1987) or Von Eckardt (1995) emphasize a surprisingly unitary view of the theoretical commitments of the discipline, such as the cognition-as-computation metaphor (for a similar point, see Goldstone, 2019), the role and



nature of mental representations, or the unit of analysis of cognition. These, among other considerations (e.g., methodological: Cooper, 2019), are the commitments around which disciplinary consensus seems to have weakened with the appearance of “alternative” frameworks for studying cognition (e.g., Chemero & Silberstein, 2008; Newen et al., 2018).

Thus, pluralism or divergence in cognitive science, whether feature (Bender, 2019) or bug (Núñez et al., 2020), is a relatively new phenomenon emerging from decades of previous work following alternative theoretical assumptions (Gibson, 1979; Hutchins, 1995; Port & Van Gelder, 1995; Rumelhart, McClelland, & Group, 1986; Varela, Thompson, & Rosch, 2016; for reviews, see Dale, 2008; Dale, Dietrich, & Chemero, 2009). This could explain concerns about a lack of a “cohesive conceptual core” like those expressed in Núñez et al. (2019, 2020). These authors note the “striking lack of a core and consistency in the curriculum of universities and colleges that grant bachelor’s degrees in cognitive science” (Núñez et al., 2020, p. 800). Although speculative, it is possible that what was seen as the conceptual canon of cognitive science, and thus what was reflected in its educational curricula, was more coherent and unified in the decades preceding the rise to prominence of what we previously referred to as “alternative” approaches. For example, it is hard to deny that the once foundational work of Jerry Fodor, particularly the *Language of Thought* (Fodor, 1975) and the *Modularity of Mind* (Fodor, 1983), occupies now a very different place in the canon, particularly outside of philosophy. On the other hand, the position of the early work in *Parallel Distributed Processing* (Rumelhart et al., 1986) has clearly shifted from the periphery to the core of the canon (especially with its renewed relevance in machine learning). Of course, these examples are anecdotal. However, we point out that more empirical studies on the *historical trajectory* of cognitive science may better reveal how the field came to its current state, illuminate the reasons for curricular heterogeneity, and even recommend formulations for a renewed canon (Cohen Priva & Austerweil, 2015).

Several other recent commentaries in *TopiCS* indirectly make this point by emphasizing that diversity should be expected in an evolving field (e.g., Bender, 2019; Gentner, 2019). Diversity should not be viewed as a negative feature in and of itself. And even if it were, nothing in the arguments presented so far preclude the possibility that it could be a *temporary* or *transitional* trait (Kuhn, 2012). To use one of the examples given by Núñez et al. (2020), it seems counterintuitive to deny “disciplinehood” to biology during the turn of the last century, between the publication of *On The Origin of Species* (Darwin, 1859) in the mid-19th century and the wide adoption of the “modern synthesis” in the 1940s (Mayr & Provine, 1998; Throckmorton & Hubby, 1963). With the benefit of time, we know now that declaring a “failure of biology” in that interregnum would have been a mistake. As Lakatos (1974) recognized, whether periods of change in scientific fields are regressive or not can only be judged in hindsight. In that sense, cognitive science is still a young field, and judgments of its failure have a high risk of being premature.

Obviously, there are limitations to the metrics we have described, just as there are limitations to disciplinary tallying. For example, a concern with metrics could be that *overlap* among mixtures of expertise may come from an early and successful interdisciplinary collaboration: Colleagues from distinct fields who, over the years, published together in a fruitful line of research. In addition, these measures cannot determine whether high JSD is related

to the disparity in departmental affiliation. This would require additional work relating both kinds of data. Correlations among these and any other measures would be important to assess in the future, along with further development of measures for interdisciplinarity both in journals and proceedings formats that characterize other fields (cf. Oey, DeStefano, Brockbank, & Vul, 2020; Wagner et al., 2011). Moreover, some of the fields from which researchers in cognitive science stem have different values regarding the important venues for publication. Thus, our focus on journals could be limiting our assessment of the relevant publication history of authors from, for example, computer science (with a higher focus on conference proceedings) or philosophy (a higher emphasis on books). Thus, future work should expand the sources from which the expertise of an author is measured. Other, more technical limitations to our methods related to the effect of grain size (individual journals) and normalization procedure on our results are discussed in the Supplementary Materials.

The metrics we have discussed suggest that fruitful “interdisciplinary” collaboration may be found despite, and even within, the confines of our departments. Cognitive science could “grow into” its many disciplines by embracing new collaborators who inhabit our disciplinary silos, but who have not yet applied their trade to the core questions of our field. They suggest that, despite shared departmental affiliation, it is these *mixtures of expertise* that represent the spirit of its definition. At the very least, they imply that it may be useful to reevaluate our definition of interdisciplinarity to better fit the reality of 21st-century cognitive science.

## Notes

- 1 Updated information on the API, now hosted by Clarivate Analytics, can be found here: <https://clarivate.com/webofsciencelgroup/>.
- 2 See Supplementary Materials for an exploration of the part of the semantic space that each theory carves out. See also Contreras Kallens and Dale (2018) for more on the representation of the theories and a more extensive interpretation and discussion of these models.

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### Supporting Information

Additional Supporting Information may be found online in the supporting information tab of this article:

**Fig. S1.** Correlation between the different measures of each article.

**Fig. S2.** Estimated marginal means along with 95% confidence intervals of different measures of divergence in publication history for different journals.

**Fig. S3.** Silhouette index for all values of  $k$  between 50 and 6000.

**Fig. S4.** Bootstrapped distribution of each theory for each journal.

**Fig. S5.** Word clouds resulting from the varimax rotation for each theory.