A Scientometric Approach to the Integrated History and Philosophy of Science: Entrenched Biomedical Standardization and Citation-Exemplar

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Abstract

Is Kuhn's notion of exemplar applicable to ongoing biomedical sciences? Many philosophers may be skeptical because Kuhn's cases are mostly from physics and chemistry. However, how do philosophers test the above (non-)applicability directly? We will use examples to illustrate a scientometric approach to the integrated history and philosophy of science (SciHPS) and argue that SciHPS can provide an empirical basis to empirically test and revise a philosophical concept questioned for its applicability to biomedical sciences. This paper will build on Yan, Tsai, and Huang's (2021) heart-rate variability (HRV) case study to examine the biomedical changes within the HRV community from 1970 to 2022. We will investigate how a Task Force standardizes and entrenches methodological standardizations, and argue that some of Task Force's methodological standardizations are tool-afforded by an algorithm. These tool-afforded aspects further explain why an HRV method is robustly dominant in the HRV community despite other HRV scholars having developed alternatives to compete with the dominant one. We will then show how to use SciHPS to empirically test and revise the Kuhnian concept of exemplar into a concept of citation-exemplar that better captures the above tool-afforded aspects of standardizations.

Keywords: Heart-rate variability, Biomedical, Scientometrics, Kuhn, Exemplar, Citation, Standardization, Tool-afforded, Fast Fourier Transform

1. Introduction

Biomedical sciences are fast-growing fields with unprecedented speed of research outputs, especially in the quantities of papers. Philosophers aiming to study ongoing biomedical changes face challenges due to three types of limitations. The first limitation is conceptual. Most philosophers are trained and armed with the conceptual tools they learned from studying philosophical literature, such as the seminal work from Thomas Kuhn (1962/1970) on concepts of exemplar, disciplinary matrix, paradigm shift, and so on. However, almost all of Kuhn's cases are from physics and chemistry. We need clarification on what extent Kuhn's conceptual tools apply to biomedical changes. Similarly, for any philosophical concepts or views of scientific changes, some (empirical) analyses of the ongoing biomedical literature bodies are required to support their applicability to biomedical changes.

The second is methodological. Past philosophers faced difficulties integrating philosophical generalizations with historical methods. For example, Kuhn (1977, 5) points out that historians of science and philosophers of science hold different goals when investigating scientific change. Historians aim to produce historical narratives of particulars and events, whereas philosophers aim to formulate universal or lawlike generalizations. Is it possible to achieve two goals simultaneously with one set of practice? Kuhn's answer is negative. He thinks practicing the history of science (HS) and philosophy of science (PS) simultaneously is like perceiving the duck-rabbit illusion. Just as one cannot see a duck and a rabbit simultaneously in the duck-rabbit illusion, Kuhn thinks one cannot practice HS and PS simultaneously.

However, the situation in studying the ongoing biomedical changes is different. Many philosophers need methods other than historical methods to handle large-scale and digitalized biomedical literature to assist their philosophical analyses. Without additional methods, the best they can do is to apply their conceptual analysis skill to one or a few concrete contemporary case studies. The limitation of this type of case study is that, even if the case study provides insight, the case study on its own is insufficient to answer the question of how generalizable the insight is within and beyond the targeted community (Chang 2012; Morgan 2012, 2014, 2019; Ankeny 2007, 2011; Pietsch 2016; Currie 2015).

Furthermore, philosophers working on case studies also face another related challenge. Before they can show the insight of a case study, there is a prior issue regarding how the case study is selected in the first place. Suppose philosophers aim to use a case study to understand some robust and significant scientific changes in a given community. In that case, they should have a way to prove that the case study represents a robust and significant scientific change for the community. However, more than conceptual analysis is needed to provide the kind of literature evidence to prove the significance of the case study. Philosophers generally need more methodological tools to provide such literature evidence. This is the third methodological limitation for philosophers studying ongoing biomedical changes.

This paper aims to illustrate ways of integrating extant scientometric tools with content-based analyses and how they help philosophers overcome the above limitations and empirically test and revise some philosophical concepts. We call this approach "a scientometric approach to the integrated history and philosophy of science" (SciHPS for short). This paper will use the

Kuhnian concept of exemplar as an example to show how a philosophical concept can be empirically tested and revised in the context of ongoing biomedical literature by applying SciHPS. Moreover, the Kuhnian example will illustrate how to empirically test and revise a concept that has been questioned for its applicability to biomedical sciences. It is important to clarify that we are not inventing a new scientometric method or tool but proposing an interdisciplinary approach that integrates extant scientometric tools with philosophical analysis styles.

Scientometrics concerns the quantitative features of scientific literature, research, and community. It applies or develops various informational techniques or tools to measure and analyze the impact of scientific articles and journals, ways of understanding scientific citations, and how to apply their measurement results to policy and management contexts (Leydesdorff & Milojević 2013). Some scholars in scientometrics have developed a citation-based quantitative tool to help investigate the structure and changes of a scientific community (Small 1973; Marshakova 1973; Schneider 2006; Chen et al. 2010; Chen 2013 & 2020). Some have applied citation-based methods to test and investigate philosophical concepts of scientific changes, such as the Kuhnian idea of paradigm shift (Marx and Bornmann 2010; Marx and Bornmann 2013). However, because of the complexity involved in what citation counts measure (Bornmann & Daniel 2008; Tahamtan & Bornmann 2018; Tahamtan & Bornmann 2019), applying scientometric tools to study scientific changes is not as straightforward as one might think. Interpreting the meaning, reasons, and motivation of citing behaviors is challenging. One must master some background or contextual understanding of the literature to interpret better why and how an article is cited. This is partly why it is fruitful and essential to integrate scientometric tools with some other content-based and context-based analyses.

Our novelty in this paper lies in showing how integrating various scientometric tools and content-based analyses allows philosophers to investigate why, when, what, and how the standardization of scientific practice in a given biomedical field is established and entrenched. Between 2018 and 2023, there is an increased number of philosophical articles engaging in SciHPS (Zou & Laubichler 2018; Gibson & Ermus 2019; Yan, Tsai, Huang 2021 and 2022; Mizrahi 2020 & 2021; Malaterre, Lareau, Pulizzotto & St-Onge 2020; Radomski, Šešelja, Naumann 2020; Allen & Murdock 2022; McLevey 2018; Khelfaoui et al. 2021; Yan and Liao 2023). It shows that philosophers are already experimenting with the potential of integrating scientometric tools with philosophical analyses to address issues in the integrated history and philosophy of science. A novel contribution we aim to make in this paper is to show how to test and revise a philosophical concept empirically.

To the above goals, the paper is structured as follows. Section 2 will review Yan et al.'s (2021) HRV case study. In section 3, we will extend their case study and show our original literature data to argue that HRV standardizations involve a task force's choice of epistemic values and that the entrenchment of the HRV standardization practice is heavily biased by a particular technological tool. Section 4 will illustrate how SciHPS can help empirically test and revise a philosophical concept such as the Kuhnian concept of exemplar. We will propose to revise the Kuhnian concept of exemplar to the concept of citation-exemplar. Section 5 will conclude with our methodological suggestions for philosophers to study ongoing biomedical changes.

2. The Case Study of Heart-Rate Variability

Heart-rate variability (HRV) is a physiological phenomenon involving interval variations between consecutive heartbeats or heart rates. The literature on HRV has proliferated in the past 50 years. Scientists and clinical practitioners value the HRV research for its potential applications in observing how sympathetic and parasympathetic nervous systems interact with each other (Rajendra Acharya et al. 2006, 1031) and how it correlates with cardiovascular and different types of diseases (Kleiger et al. 1987; Malik et al. 1989; Bigger et al. 1992). The HRV research community is cross-disciplinary, involving physiology, neuroscience, biomedical engineering, clinical medicine, and so on.

Yan et al. (2021) used quantitative tools to select a case study out of the growing literature from this cross-disciplinary biomedical community. First, they performed citation analysis to determine 40 highly-cited articles based on the citation data from the Web of Science database. One review article, RA-11, has a significantly higher citation than the other 14 review articles and 25 original research articles (Yan, Tsai, and Huang 2021, 9597, Figure 1). RA-11 was cited 6460 times during Yan et al.'s analysis, published in 1996, and authored by The Task Force of the European Society for Cardiology and the North American Society of Pacing and Electrophysiology (the Task Force for short).

Having identified a uniquely highly-cited RA-11, they performed a categorization analysis using the data from another PubMed database. They retrieved 19,795 articles on HRV published between 1970 and 2016 from the PubMed database. This helped them investigate whether the significance of the high-citation number of RA-11 is replicated in this second set of studies. They categorized 19,795 articles according to the following three categories: (A) foundational research on relevant mechanisms or technological advances, (B) correlation to cardiovascular disease, and (C) correlation to non-cardiovascular disease (Yan, Tsai, and Huang 2021, 9598, Figure 2). The categorization results are plotted chronologically and reveal that there is a crucial change of pattern after the year 1996. Type C research decreased before 1996 and increased between 20% to 30 % after 1996. Type B research increased before 1996 and decreased by 20% after 1996. Type A research decreased and increased before 1996 and then decreased by 15 % after 1996. In short, RA-11's publication is correlated with the above patterns of change in research trends.

To further test the epistemic quality of their categorization results, they perform another set of quantitative analyses to see if the results converge with their categorization analyses. They performed word-frequency analysis, a kind of text analytics that combines computational, statistical, and linguistic techniques to analyze text data. The article titles of all 19,795 articles above are analyzed based on how many times a word appears. They visualized the five most frequent words in the article titles of every thousand articles and arranged the data chronologically (Yan, Tsai, and Huang 2021, 9599, Figure 3). This way of visualizing their word-frequency results is crucial because they can compare their categorization results with their word-frequency results. Exercise, sleep, and stress are the three words related to non-clinical applications. Between 1996 and 2001, 'sleep' showed up. After 2001, 'exercise,' 'sleep,' and 'stress' became the three most frequent words. As a result, there is a consistent pattern between the categorization and word-frequency results. This is consistent with the patterns shown in the categorization results: Type C research, i.e., non-clinical application research, increased by 30 %, while Type A and Type B decreased by 15% to 20%.

Yan et al. (2021) used the above three sets of analyses to justify their selection of RA-11 as a case study for investigating why and how the identified changes in research patterns happened before and after 1996. Having done that, they performed a practice-based analysis of the contents of RA-11, i.e., using types of practice as their unit of analysis to characterize what RA-11 has achieved. Their results show that RA-11's two main achievements are (1) standardizing procedures and methods for measuring HRV and processing HRV signals and (2) standardizing two HRV clinical applications. In other words, the standardization of HRV practices is correlated with the subsequent increase of non-clinical applications in research patterns in the HRV community.

3. Entrenching the HRV Standardizations

However, as Yan et al. (2021) noted, their data is insufficient to ground any further substantive interpretations as to why the above correlation exists. More than the high citation number of RA-11 is needed to support that subsequent scholars cite RA-11 for following their standardizations. More empirical data is required to prove this.

Yan, Tsai, and Huang (2022) conduct another set of analyses to investigate whether scholars cite RA-11 for methodological reasons. They utilize several information tools. One is to find PDF files of the articles computationally. Another is to convert each PDF file into XML files with the same tagged article elements, e.g., headers and references. The other is to locate each in-text citation of RA-11 within XML files and classify each in-text citation under the four categories: (1) introduction, (2) methods, (3) results, and (4) discussion or conclusion. They obtained the citation data of RA-11 from the Web of Science and found 8,722 articles citing RA-11 as of April 20, 2020. Due to the limitation of their information tools, they can only successfully classify 2,240 articles out of 8,722. Their result is that 349 articles are classified under the method category. Yan et al. further provided four in-text citation examples from the identified 349 articles:

> HRV analysis was performed in the frequency domain (PSA) on each of three 5-minute ECG recordings (baseline, active standing, paced breathing), in accordance with the guidelines of the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (Nicolini et al. 2014, 4);
>
> HRV was analyzed using a computer program based on commercially available software (LabVIEW, National Instruments, Austin, TX, U.S.A.), which meets the recently published criteria of HRV measurement, [i.e., those from RA-11] (Keyl et al. 1997, 337);
>
> Time-domain variables were evaluated in accordance with the guidelines of the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (Weissman et al. 2009, 119);

> Moreover, the experimental procedures were performed between 1 and 4 P.M. to standardize the protocol [according to RA-11] (Raimundo et al. 2013, 489). (2022, 78)

Though Yan et al.'s (2022) dataset is not perfect but informative, it at least provides evidence beyond the mere citation number to support that scholars cite RA-11 for methodological reasons related to the HRV standardizations of RA-11 or strictly for following the standardizing practices from RA-11 as the above four examples have shown.

3.1 The Distribution of the Two Types of HRV Measurement Methods

HRV research community utilizes two major types of measurement methods. One is the time domain methods (TDMs), and the other is the frequency domain methods (FDMs) (Task Force 1996, 355-362). Most of the standardizing work of RA-11 was spent on standardizing measurement and recording practices in TDMs and FDMs. Here, we will provide a new set of evidence to investigate further the methodological aspects of HRV standardizations.

Our first dataset focuses on the distribution of TDMs and FDMs in the HRV research community. We aim to depict the overall distribution of TDMs and FDMs to lay down the first basis for investigating the role of RA-11 for the methodological changes in the HRV community.

We use the PubMed database and its search functions to find articles related to HRV and its measurement methods. Our keywords for TDMs and FDMs are informed by RA-11. Below is our query method:

> Query Database: PubMed
> Query Data: 2023/02/01
> Query Period: 1990/01/01~2022/12/31
> Query Strategy:
> 1. For all HRV articles: "heart rate variability."
> 2. **[Time]**
>   For HRV articles related to TDMs: "heart rate variability" and ("SDNN" or "SDANN" or "NN50" or "pNN5" or "RMSSD")
> 3. **[Frequency]**
>   For HRV articles related to FDMs: "heart rate variability" and (LF or HF or "low frequency" or "high frequency")
> 4. **[Time & Frequency]**
>   For HRV articles related to both TDMs and FDMs: ("heart rate variability" and (LF or HF or "low frequency" or "high frequency")) and ("heart rate variability" and ("SDNN" or "SDANN" or "NN50" or "pNN5" or "RMSSD"))
> 5. **[Time-Frequency]**
>   For HRV articles related to a hybrid method (i.e., use the time and frequency domains analysis simultaneously): "heart rate variability" and ("short time Fourier" or "short term Fourier" or "windowed Fourier" or "time-dependent Fourier" or "STFT" or "short time window Fourier" or "SWFT" or "wavelet" or "Hilbert–Huang" or "HHT")

6. **[Others]**
   For HRV articles related to methods other than FDMs and/or TDMs: “heart rate variability” and (“autoregressive” or “fractal” or “chaos”)

PubMed database’s search function searches only the titles, abstracts, and keywords, not full texts. There are 22,508 articles related to HRV, and only 47% (10,603) of the articles’ titles, abstracts, or keywords have the above keywords we queried. Of these 10,603 HRV articles, 60% (6363) are FDM-related papers, significantly outnumbering other categories.

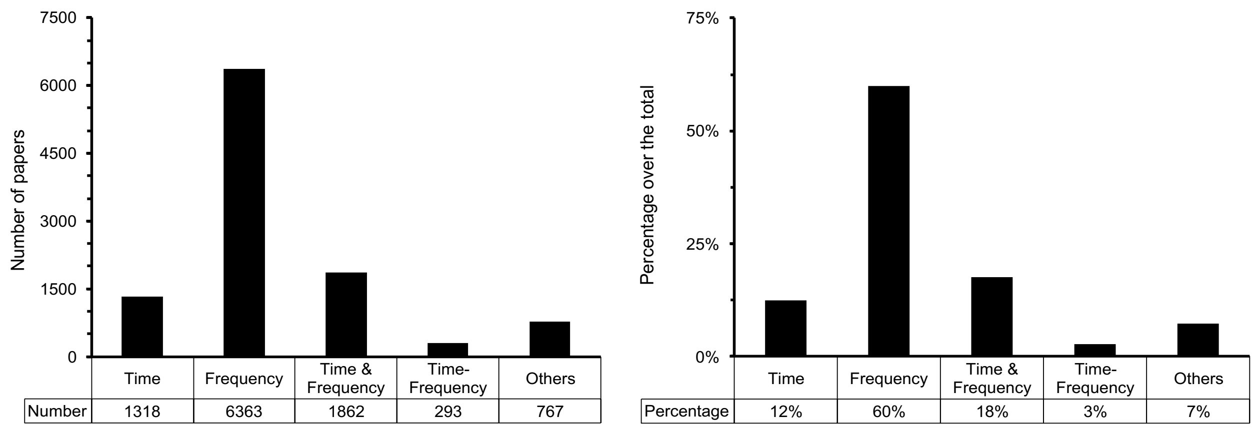


Figure 1. The distribution of different types of methods.

We sample 10,603 articles from the following three periods: (1) 1990~1995, five years before RA-11 was published, (2) 1998-2003, five years after RA-11 was published, (3) 2016-2021, the recent five years. By comparing these three periods, we found that FMDs were the dominant methods before RA-11’s publication and continued to be so throughout the three periods.

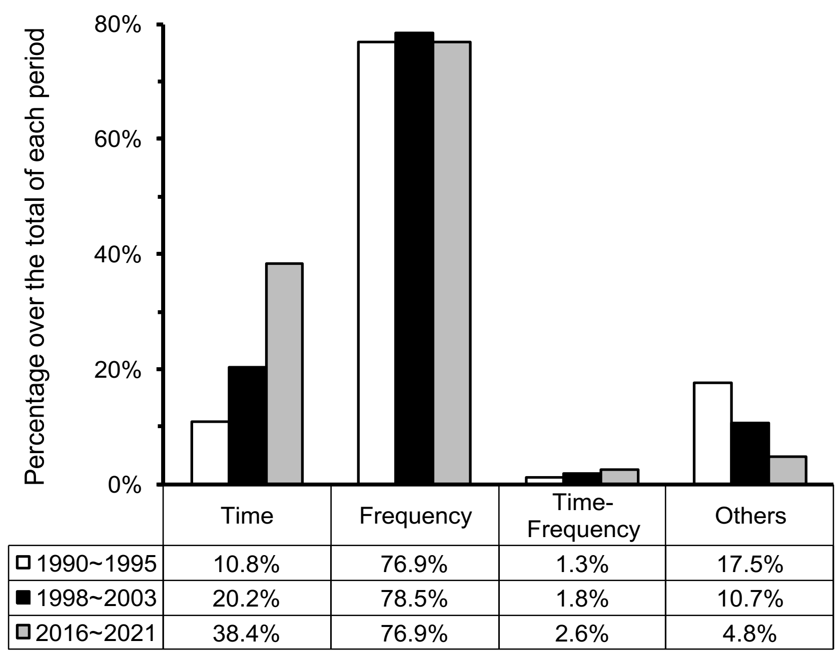


Figure 2. The distribution of different methods from three different periods.

From Figure 2, we did see the effect of increasing TDMs after RA-11 was published. The standardizing work of RA-11 is probably part of the reason. However, RA-11's standardization work cannot account for the dominance of FDMs before RA-11 was published. Other factors drive the robust dominance of FDMs before RA-11. Moreover, standardization alone cannot explain the robust dominance of FDMs after RA-11 since RA-11 standardizes both FDMs and TDMs.

3.2 RA-11's Tool-Afforded and Epistemic Judgments of FDMs

So far, we have found two interesting patterns. One is that FDMs significantly outnumber TDMs and other methods in general. The other is that FDMs were already dominant before RA-11's standardizing work and remained dominant to roughly the same degree. This robust dominance of FDMs seems to involve factors other than the fact that RA-11 standardized HRV practices. In other words, the correlation between RA-11's standardizing work and the subsequent changes in research patterns cannot be understood only in how RA-11's standardizing role guides the subsequent research. There are some other factors involved.

The task force presents their standardizing results in the order of TDMs, FDMs, and the correlation and differences between TDMs and FDMs (355-362). By looking into how RA-11 reports its standardizing results, we found that the report involves the judgments regarding the epistemic values of FDMs, i.e., how FDMs are based on an algorithm that has simplicity and high processing speed and how FDMs are easier to use than TDMs if some preconditions are met. In the following, we will show our narrative analysis of the paragraphs from RA-11 to show the above judgments. We will first compare the paragraphs for TDMs and FDMs, then focus on the paragraphs for the correlation and differences.

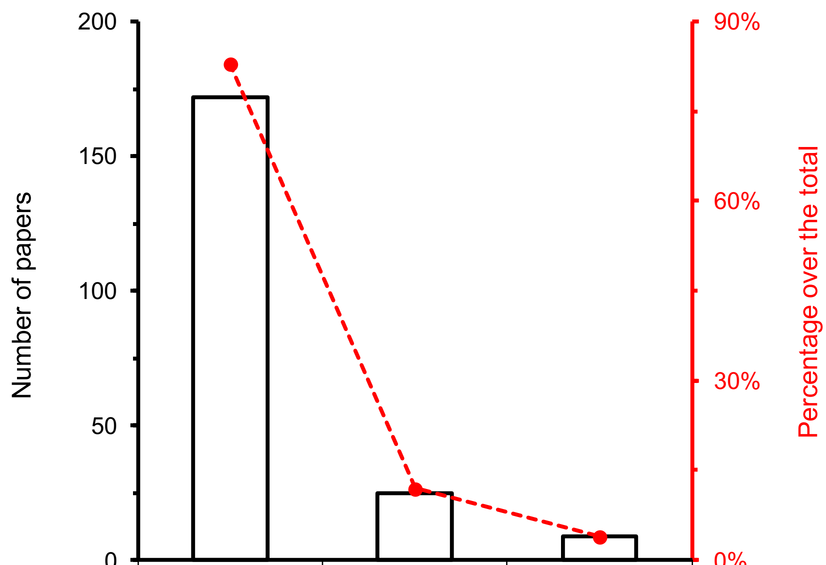
Comparing how the task force wrote the paragraphs of TDMs and FDMs, one crucial difference is that the TDM paragraphs involve no algorithms. However, the FDM paragraph involves an algorithm called Fast Fourier Transform (FFT). In the TDM paragraphs, the task force's standardizing work focuses on standardizing measures about the statistical and geometric methods (Table 1, p. 358). By contrast, in the FDM paragraphs, the task force spent some space conveying the advantages of FFT-based FDMs: "The advantages…are: (a) the simplicity of the algorithm employed (Fast Fourier Transform — FFT — in most of the cases) and (b) the high processing speed" (p. 358). Furthermore, the section title related to the standardizing work in the FDM paragraphs is named "[a]lgorithmic standards and recommendations," it is the only section in RA-11 that ties the standardizing work with an algorithm. It is reasonable to say that the task force's judgment is tool-afforded in that FFT as a technological tool affords some possible uses for HRV scholars and enables them to obtain simple and intuitive understandings of the data and achieve high processing speed.

In the section titled "[c]orrelation and differences between time and frequency domain measures," the task force further conveys two judgments of how and why FDMs are better than TDMs. One is that, for the same set of recording data, more extant theoretical knowledge and experience can ground the physiological interpretations of FDM-based measures compared to TDM-based measures (362). The other is that, excluding some special cases, FDMs can be treated as equivalent to TDMs because FDM and TDM measures are strongly correlated due to the mathematical and physiological relationships (362). Because of this, the task force favors FDMs over TDMs based on the reason that FDMs are "easier to perform" (362).

Based on the above narrative analysis of the paragraphs in which the task force presents and reports their standardizing work of TDMs and FDMs, we can conclude that the task force has a stronger preference toward FDMs over TDMs because they explicitly expressed their epistemic preference of FDMs on the ground of simplicity, high processing speed, easy-to-use, and richer theoretical knowledge and experience to rely on.

3.3 How Proponents of Non-FFT-based Argue

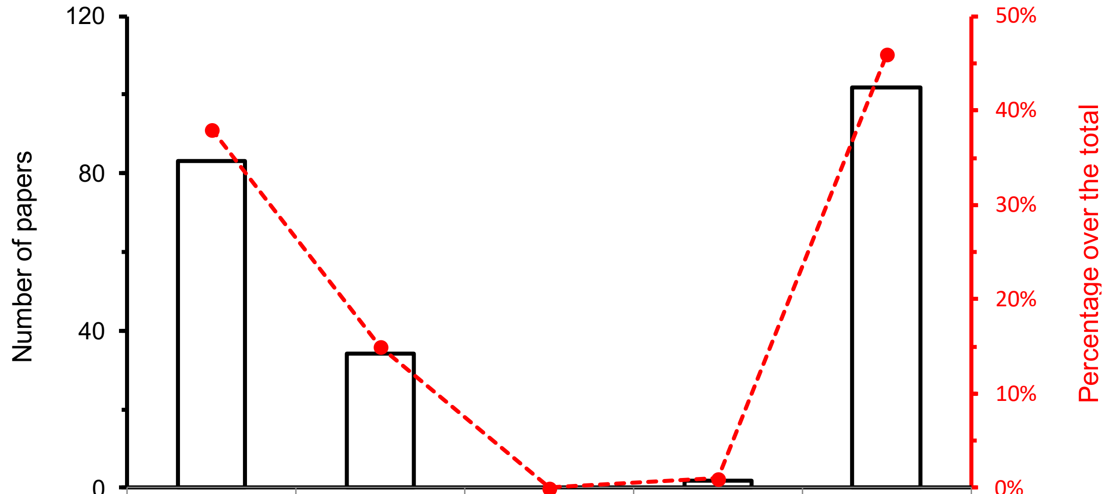
In this section, we present another dataset regarding non-FFT HRV methods. The FFT algorithm is what most FDMs methods use. RA-11 has listed FFT's main advantages: simplicity, high-processing speed, ease to use, and richer theoretical knowledge. However, FFT is not the only available algorithm in the HRV community. Some scholars have developed other algorithms to overcome the problems of FFT in processing HRV signals. We query the PubMed database with the following keywords: heart-rate variability and (short-time Fourier transform or wavelet or Hilbert-Huang transform). We found 348 articles, downloaded all the PDFs, and manually went through all the articles to remove duplicate records, review articles, and FFT-based and other methods. This process results in 206 articles, 172 articles using wavelet, 25 articles using short-time Fourier transform (STFT), and nine articles using the Hilbert-Huang transform (HHT).



	Wavelet	STFT	HHT
Number	172	25	9
Percentage	83%	12%	4%

Figure 3. The distribution of the three non-FFT-based methods: Wavelet, STFT, and HHT

We then went through each article to locate where and what reasons each author gave to explain why they chose or defended wavelet, STFT, or HHT. The following figure shows that most authors gave their reasons in the introduction and method sections.



	Introduction	Methods	Results	Discussions	None
Numebr	83	34	0	2	102
Percentage	38%	15%	0%	1%	46%

Figure 4. Where reasons are given to explain the authors' choice of wavelet, STFT, or HHT

We copied all the sentences representing the authors' reasons for using or defending wavelet, STFT, or HHT and analyzed the word frequency of all the copied texts. The following two word-cloud figures show the most frequent words in the texts we have identified and analyzed from the introduction and method sections.

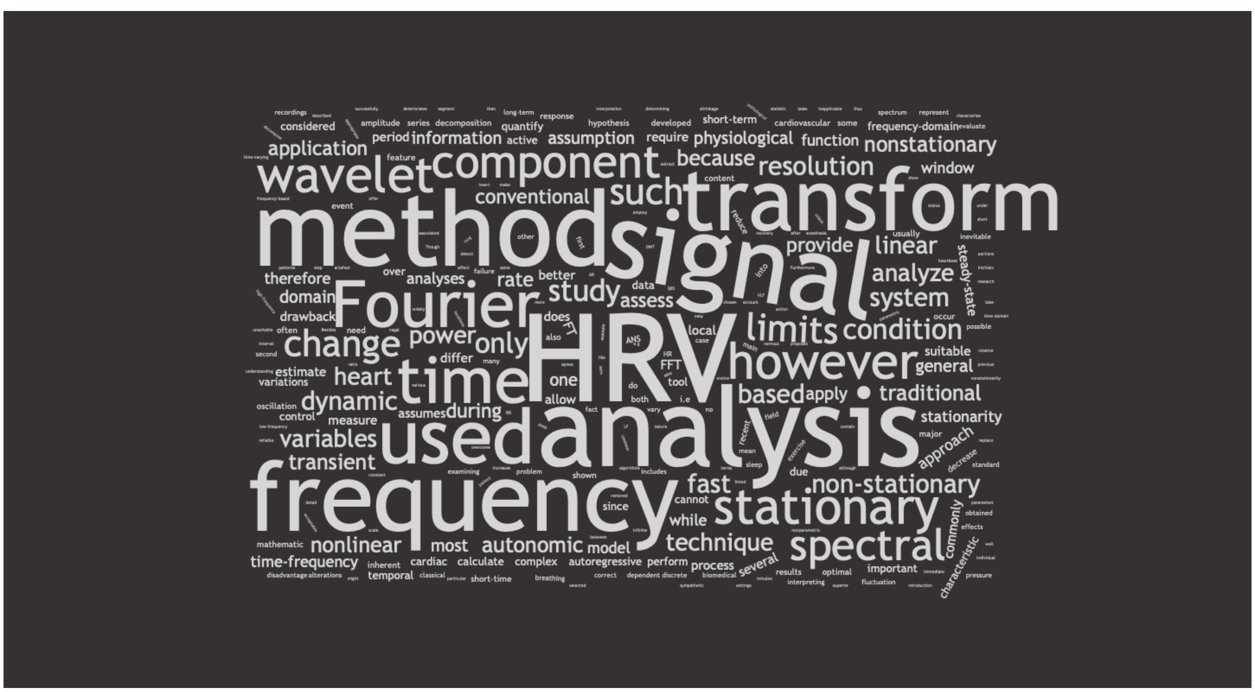


Figure 5. The word frequency analysis results from the introduction sections of the 206 articles using wavelet, STFT, or HHT.

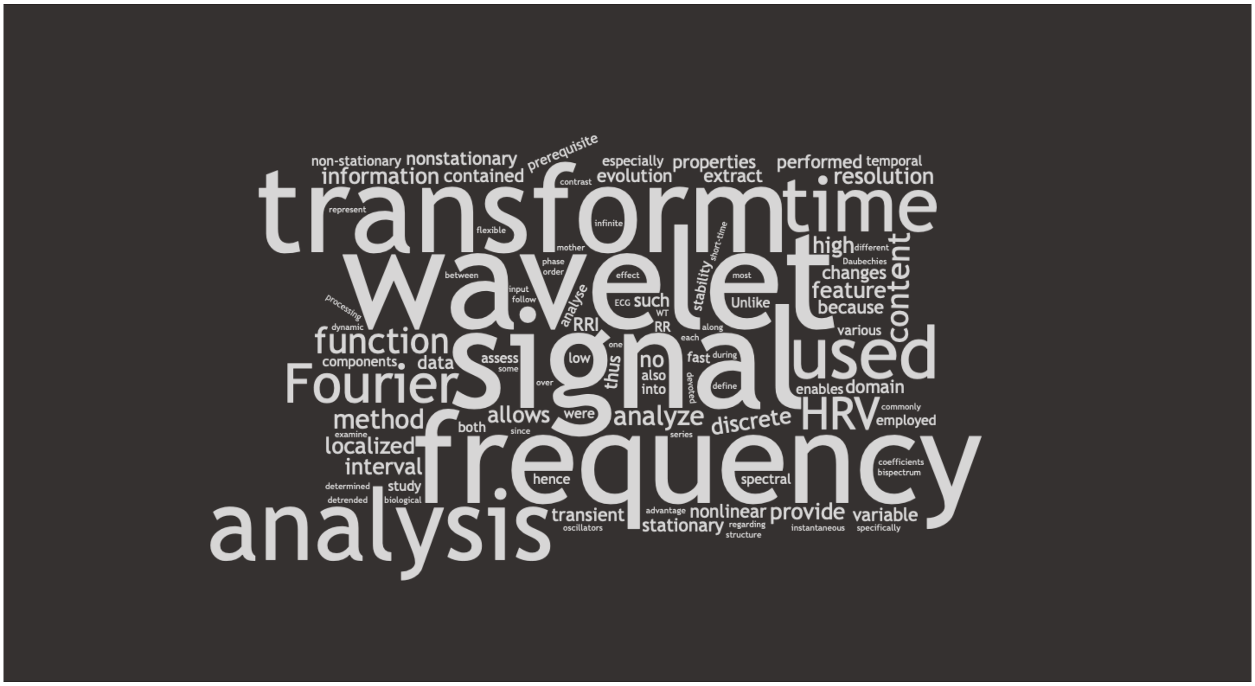


Figure 6. The word frequency analysis results from the method sections of the 206 articles using wavelet, STFT, or HHT.

The above figures show that, other than the more generic terms and jargon such as method, analysis, frequency, transform, signal, time, component, HRV, wavelet, and Fourier, terms like stationary, non-stationary, nonstationary, dynamic, transient, and nonlinear are all frequent words. This set of terms is related to a methodological issue in HRV research and is consistent with what we have learned from reading RA-11. RA-11 did report the most discussed problem with FDMs: “The problem of ‘stationarity’ is frequently discussed with long-term recordings [using FDMs].” (Task Force 1996, 359). In a nutshell, this stationarity problem is that the relevant physiological mechanisms underlying the critical FDM-based measures cannot be considered stationary during the 24-h period. However, FDMs can, at best, provide averaged data to capture aspects of HRV. The averaged data obscure the detailed dynamic information regarding HRV.

Below we present 29 examples from our dataset to illustrate further how proponents of non-FFT-based methods reason with the problem of stationarity:

No.	Year	Article Information	Quotations
1	1999	Pichot, et al. (1999). Wavelet transform to quantify heart rate variability and to assess its instantaneous changes. *Journal of*	Fourier transform is the one most commonly chosen (27, 28) but one that is, however, limited to stationary signals. With this mathematical transform, global representative indexes of heart

		Applied Physiology (Bethesda, Md.: 1985), 86(3), 1081–1091.	rate variability have to be calculated as a set of cumulate spectrum powers contained in a given number of R wave-to-R wave (R-R) intervals, which prevents temporal localization of sudden changes in the behavior of the R-R signal. To overcome these limitations, we applied wavelet transform, which offers two complementary interesting features (2, 9, 16, 32). (1081)
2	2005	Kawaguchi, et al. (2005). Cardiovascular and autonomic nervous functions during acclimatization to hypoxia in conscious rats. *Autonomic Neuroscience: Basic & Clinical*, 117(2), 97–104.	However, although FFT is commonly used to analyze variability, it has a limited ability to assess transient autonomic alterations (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). Unlike FFT, the wavelet transform (WT) technique provides a reliable assessment of the dynamics of non-stationary signals (Hammill et al., 1979; Murasato et al., 1998). (98)
3	2015	Kenwright, et al. (2015). The discriminatory value of cardiorespiratory interactions in distinguishing awake from anaesthetised states: A randomised observational study. *Anaesthesia*, 70(12), 1356–1368.	Complex oscillations can often be decomposed into their individual oscillatory components using the Fourier transform. Formally, however, this can be done only when the signals are periodic, which implies that, for example, mean heart rate is constant over time. In reality, this is not the case. Therefore, we need methods that reveal the time-variability of the constituent oscillations. (1357)
4	2016	Akar, S. A., Kara, S., & Bilgiç, V. (2016). Investigation of heart rate variability in major depression patients using wavelet packet transform. *Psychiatry Research*, 238, 326–332.	Fourier transform (FT) is the oldest and the simplest power spectrum estimation method. However, the usefulness of the FT only in the stationary signals and the inability of this technique to track separate time events in diverse frequency components have been accepted (Gamero et al., 2002). (327)
5	2016	Niizeki, Kyuichi, and Tadashi Saitoh. "Analysis of cardiorespiratory phase coupling and cardiovascular autonomic responses during food ingestion." Physiology & Behavior 159 (2016): 1-13.	For determining frequency-domain HRV indexes, a short-time Fourier transform was performed. This method has been used to estimate the time course of transient changes in HRV and was demonstrated to be effective in quantifying the dynamic pattern of the HRV during nonstationary conditions. (8)

6	2016	Rawal, K., Saini, B. S., & Saini, I. (2016). Design of tree structured matched wavelet for HRV signals of menstrual cycle. *Journal of Medical Engineering & Technology*, 40(5), 223–238.	In the frequency domain methods, Fast Fourier Transform (FFT) is the most widely used technique. However, it is not suitable for analysing non-stationary signals like HRV because they have no time resolution. (223)
7	2016	Takahashi, M., Nakamoto, T., Matsukawa, K., Ishii, K., Watanabe, T., Sekikawa, K., & Hamada, H. (2016). Cardiac parasympathetic outflow during dynamic exercise in humans estimated from power spectral analysis of P-P interval variability. *Experimental Physiology*, 101(3), 397–409.	A Fourier transform, which is the most commonly used method to analyse R–R interval variability, is not able to assess the dynamic changes in R–R interval variability because of limitations inherent in the stationary hypothesis (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). This approach will not be applicable when examining R-R interval variability in non-stationary conditions, such as exercise. (399)
8	2016	Tejman-Yarden, S., Levi, O., Beizerov, A., Parmet, Y., Nguyen, T., Saunders, M., Rudich, Z., Perry, J. C., Baker, D. G., & Moeller-Bertram, T. (2016). Heart rate analysis by sparse representation for acute pain detection. *Medical & Biological Engineering & Computing*, 54(4), 595–606.	For acute events, the Wavelet transform (WT) could be better suited due to its properties of representing signals with a finite number of sudden short duration and time localized changes that differ from the baseline harmonics. (596)
9	2016	Wachowiak, M. P., Hay, D. C., & Johnson, M. J. (2016). Assessing heart rate variability through wavelet-based statistical measures. *Computers in Biology and Medicine*, 77, 222–230.	Furthermore, as traditional frequency-based methods employ the FT, which integrates (averages) over all sampled time, it is difficult to assess when the changes in the heart rate are occurring. It is particularly problematic for detecting transient events, even when phase angles (which, as modular measures, cannot pinpoint times of events) are used. (223)
10	2017	Sakazaki, S., Masutani, S., Iwamoto, Y., Asano, Y., Miyamoto, A., Ishido, H., Tamura, M., & Senzaki, H. (2017). A 1-year-old boy with long pauses caused by paroxysmal atrioventricular block and sinus arrest: Vagal reflex and effect of pacing. *Journal of Electrocardiology*, 50(2), 203–206.	We employed wavelet analysis, which enables high time resolution in seconds for HRV, and quantified the high-frequency (HF: 0.15–0.4 Hz) parasympathetic activities. (204)

11	2017	Ticcinelli, V., Stankovski, T., Iatsenko, D., Bernjak, A., Bradbury, A. E., Gallagher, A. R., Clarkson, P. B. M., McClintock, P. V. E., & Stefanovska, A. (2017). Coherence and Coupling Functions Reveal Microvascular Impairment in Treated Hypertension. *Frontiers in Physiology*, 8.	The WT also provides logarithmic frequency resolution (not achievable with a Fourier transform), thus yielding an appropriate representation of the low frequency spectral structure. (5)
12	2017	Xin, Y., Zhao, Y., Mu, Y., Li, Q., & Shi, C. (2017). Paroxysmal atrial fibrillation recognition based on multi-scale Rényi entropy of ECG. *Technology and Health Care*, 25(S1), 189–196.	The main methods used in HRV analysis are time-domain, frequency domain, and non-linear. The time-domain method proposes limitations on the fluctuation of heart rate. The frequency-domain method is solely based on a steady model; therefore it cannot show important detailed characteristics of HRV. (189)
13	2018	Amezquita-Sanchez, J. P., Valtierra-Rodriguez, M., Adeli, H., & Perez-Ramirez, C. A. (2018). A Novel Wavelet Transform-Homogeneity Model for Sudden Cardiac Death Prediction Using ECG Signals. *Journal of Medical Systems*, 42(10), 176.	DWT has been found to be effective for processing of signals with transient properties such as EEG and ECG signals. (4)
14	2018	Ashtiyani, M., Navaei Lavasani, S., Asgharzadeh Alvar, A., & Deevband, M. R. (2018). Heart Rate Variability Classification using Support Vector Machine and Genetic Algorithm. *Journal of Biomedical Physics & Engineering*, 8(4), 423–434.	Different mathematical methods exist to analyze HRV. The most common one is the Fourier transform which is limited to stationary signals. Wavelet transform analysis is one of the choices which can help to quantify HRV in non-stationary conditions. (424)
15	2018	Fauchon, C., Pichot, V., Faillenot, I., Pommier, B., Garcia-Larrea, L., Peyron, R., & Chouchou, F. (2018). Contextual modulation of autonomic pain reactivity. *Autonomic Neuroscience*, 212, 28–31.	This wavelet analysis of the RRI signal enables to follow the time evolution of each frequency contained in the RRI signal, using the mother function Daubechies 4. (29)
16	2018	Gilfriche, P., Arsac, L. M., Daviaux, Y., Diaz-Pineda, J., Miard, B., Morellec, O., & André, J.-M. (2018). Highly sensitive index of cardiac autonomic	The main drawback in assessing cardiac autonomic control using classical frequency-based HRV analysis is that interindividual and situation-dependent breathing patterns are usually not considered. It is then implicitly assumed that

		control based on time-varying respiration derived from ECG. *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology*, 315(3), R469–R478.	breathing variations do not fundamentally impact the correct quantification of distinct sympathetic and vagal control. (R470)
17	2018	Singh, R. S., Saini, B. S., & Sunkaria, R. K. (2018). Detection of coronary artery disease by reduced features and extreme learning machine. *Clujul Medical* (1957), 91(2), 166–175.	Nonlinear techniques are more sensitive than linear methods for recognizing and comprehending the abnormalities of HRV. (167)
18	2018	Wachowiak, M. P., Wachowiak-Smolíková, R., Johnson, M. J., Hay, D. C., Power, K. E., & Williams-Bell, F. M. (2018). Quantitative feature analysis of continuous analytic wavelet transforms of electrocardiography and electromyography. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, 376(2126), 20170250.	Frequency analysis based on the Fourier transform (FT) is generally the first step in determining frequency content. However, FT assumptions, including stationarity, do not apply to complex physiological signals, which are generally non-stationary and contain transient components. (2)
19	2018	Wang, X., Yan, C., Shi, B., Liu, C., Karmakar, C., & Li, P. (2018). Does the Temporal Asymmetry of Short-Term Heart Rate Variability Change during Regular Walking? A Pilot Study of Healthy Young Subjects. *Computational and Mathematical Methods in Medicine,* 2018, e3543048.	Besides, to explore the potential effect of nonstationary trend, wavelet detrending was performed and the above four asymmetrical indices were recalculated using the detrended data. (3)
20	2018	Wu, H.-T., & Soliman, E. Z. (2018). A new approach for analysis of heart rate variability and QT variability in long-term ECG recording. Biomedical Engineering Online, 17(1), 54.	Most of the methods applied to measure long-term HRV are based on the stationarity assumption, a common assumption in many time series techniques. While those methods could still be applied to any non-stationary time series, such as 24-48 h long-term heart rate, the results might not be directly interpretable, miss the finer non-stationary dynamics, or even misleading. (1)
21	2019	De Boer, R. W., & Karemaker, J. M. (2019). Cross-Wavelet Time-Frequency Analysis Reveals Sympathetic Contribution to	The great strength of cross analysis is that it enables one to study how spectral features evolve over time. Hence values for magnitude, BRS,

		Baroreflex Sensitivity as Cause of Variable Phase Delay Between Blood Pressure and Heart Rate. *Frontiers in Neuroscience*, 13.	phase and coherence can be determined as a function of time. (4)
22	2019	Estévez-Báez, M., Machado, C., García-Sánchez, B., Rodríguez, V., Alvarez-Santana, R., Leisman, G., Carrera, J. M. E., Schiavi, A., Montes-Brown, J., & Arrufat-Pié, E. (2019). Autonomic impairment of patients in coma with different Glasgow coma score assessed with heart rate variability. Brain *Injury*, 33(4), 496–516.	The traditional approach using the Fourier analysis for the study of spectral components of HRV has been successfully and widely used since its introduction, but strictly speaking this method is limited to the study of linear systems. (496)
23	2019	Gruszecki, M., Tkachenko, Y., Kot, J., Radkowski, M., Gruszecka, A., Basiński, K., Waskow, M., Guminski, W., Anand, J. S., Wtorek, J., Frydrychowski, A. F., Demkow, U., & Winklewski, P. J. (2019). Coupling of Blood Pressure and Subarachnoid Space Oscillations at Cardiac Frequency Evoked by Handgrip and Cold Tests: A Bispectral Analysis. *Advances in Experimental Medicine and Biology*, 1133, 9–18.	Bispectrum analysis provides information about the coupling properties between interacting oscillators. The bispectrum is a frequency-frequency domain method that arises from higher-order statistics (Jamšek et al. 2004). However, the frequency-frequency domain is still unable to track time variability. Therefore, similarly to the time-frequency analysis, time-frequency-frequency analysis leads to a proposal of wavelet-based bispectral analysis (Jamšek et al. 2004, 2007) (11)
24	2019	Kontaxis, S., Lazaro, J., Gil, E., Laguna, P., & Bailon, R. (2019). Assessment of Quadratic Nonlinear Cardiorespiratory Couplings During Tilt-Table Test by Means of Real Wavelet Biphase. *IEEE Transactions on Bio-Medical Engineering*, 66(1), 187–198.	Wavelets introduction in bispectrum field reduced time averages to a minimum, allowing the application of HOS in non-stationary biomedical signals. (188)
25	2019	Wachowiak, M. P., Moggridge, J. J., & Wachowiak-Smolíková, R. (2019). Clustering Continuous Wavelet Transform Characteristics of Heart Rate Variability through Unsupervised Learning. *2019 41st Annual International Conference of the IEEE Engineering in Medicine*	Although the Fourier transform (FT) is generally the first step in determining frequency content, such analysis is often not sufficient for nonstationary signals and those that contain transient components, necessitating the need for time-frequency techniques, including wavelet transforms. (4585)

		and Biology Society (EMBC), 4584–4587.	
26	2019	Zhao, Z., Deng, Y., Zhang, Y., Zhang, Y., Zhang, X., & Shao, L. (2019). DeepFHR: Intelligent prediction of fetal Acidemia using fetal heart rate signals based on convolutional neural network. *BMC Medical Informatics and Decision Making*, 19(1), 286.	The CWT has several outstanding merits, such as the reliable and flexible capacity to extract general and fine-grained feature information from the input signal; hence, this transform has been extensively employed in biomedical engineering to analyze non-stationary and nonlinear signals over the last decades. (4)
27	2020	Knai, K., Aadahl, P., & Skjaervold, N. K. (2020). Cardiac surgery does not lead to loss of oscillatory components in circulatory signals. *Physiological Reports*, 8(9), e14423.	We used the Morlet wavelet, which by mathematical definition is a Gaussian enveloped cosine wave, and has been widely used for investigation of biological signals, especially the ECG (Addison, 2005). (3)
28	2020	Wong, E. M., Tablin, F., & Schelegle, E. S. (2020). Comparison of nonparametric and parametric methods for time-frequency heart rate variability analysis in a rodent model of cardiovascular disease. *PLOS ONE*, 15(11), e0242147.	Importantly, ANS activity is dynamic; fluctuating over time as well as in response to various stimuli. To quantify changes in the HRV spectrum, several different time-varying or time-frequency approaches have been developed. (2)
29	2022	Battaglia, et al. (2022). Characterizing cardiac autonomic dynamics of fear learning in humans. *Psychophysiology*, 59(12), e14122.	Conventional analysis of HRV requires an observation window in the range of 2–3 minutes and some level of stationarity during this period (Akselrod et al., 1981; Chan et al., 2001; Rajendra Acharya et al., 2006; Task Force, 1996). It is, therefore, inadequate to capture transient changes in heart rate produced by the ANS [autonomic nervous system]…(2)

Table 1. Examples of how proponents of non-FFT-based methods reason with the problem of stationarity

From the above examples, one can see that the problem of stationarity is persistent up to the present time. Though HRV scholars have developed alternative algorithms to address this problem of FFT-based methods, the robust dominance of FFT-based FDMs continues.

4. An SciHPS Example: From Kuhnian Exemplar to Citation Exemplar

The above datasets show that FFT-based methods, despite the problem of stationarity, still outnumber other algorithm-based methods. Furthermore, this outnumbering pattern is consistent before and after RA-11 was published and continues even after 206 articles have tried to develop and defend alternative algorithms to address the stationarity problem.

To explain the above situation, we think it is crucial to understand the context in which the RA-11's judgment of FDMs is formed. The task force explicitly states the epistemic reasons (i.e., simplicity, high processing speed, easy-to-use, and richer theoretical knowledge) to favor the FFT-based methods despite acknowledging their inaccuracy in capturing non-stationary signals. More importantly, the Task Force made the above statements for preferring FDMs in their status as an expert group in the community. A task force in a biomedical community can be understood as an expert group in Grundmann's (2017) relational concept of experts:

> [E]xperts mediate between the production of knowledge and its application; they define and interpret situations; and they set priorities for action. Experts are primarily judged by clients, not necessarily by peers (professional or scientific); and they rely on trust by their clients. (27) [1]

The European Society of Cardiology and the North American Society of Pacing and Electrophysiology are the two academic clients conferring the task force's expert status within the relevant community. The task force in RA-11 did interpret extant research measurement methods, tools, procedures, and results; they also set priorities for further clinical and non-clinical applications. The task force's judgments thus obtain a substantial degree of trustworthiness based on their relational expertise, which is not obtainable only through an individual's skill or other credentials. Because of the type and the degree of trustworthiness regarding the judgments of FDMs, more work and effort are required for later challengers or improvers, such as the authors of 206 articles defending wavelet, STFT, or HHT, to weaken or shift the kind of social-epistemic status RA-11 has achieved.

The HRV case study we generated vis SciHPS provides a basis for historians and philosophers of science to empirically test and revise philosophical concepts for understanding patterns in biomedical sciences. Several philosophical concepts are relevant to the entrenched biomedical standardization we found, such as Funjumura's (1992) concept of standardized packages and Ankeny and Leonelli's (2016) concept of research repertoire. However, both concepts are developed initially through their biomedical case studies. By contrast, Kuhn's concept of exemplar is primarily defended with examples from physics and chemistry. It is unclear whether Kuhn's concept of exemplar applies to biomedical sciences. In the following, we aim to show how SciHPS can provide a basis to test and revise Kuhn's concept of exemplar empirically to examine the applicability of Kuhn's concept of exemplar to biomedical science.

Our starting point is how Rouse (2002, 107-108) and Shan (2020, 389-392) interpret and expand Kuhn's concept of exemplar. Both philosophers emphasize the importance of articulating the non-theoretical aspects of exemplar that are explained insufficiently or left unarticulated by Kuhn himself. Rouse (2002) interprets Kuhn's concept of exemplar as mastering "exemplary ways of conceptualizing and intervening in particular situations" (2002, p. 107). In this interpretation, the non-theoretical aspects, i.e., the acts of conceptualizing and intervening, are

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[1] For more review on the other five conceptualizations of expertise in the STS literature, please see Grundmann (2017, 32-42).

the core features used to characterize what exemplars are. Rouse (2002, 107–108) further lists typical skills acquired through mastering exemplary ways of conceptualizing and intervening:

> (1) applying concepts to specific situations
> (2) deploying mathematical tools, applying them correctly to the situation at hand, knowing their limitations, and knowing ways to circumvent those limitations
> (3) using instrumental and experimental techniques and procedures
> (4) recognizing significant opportunities to extend these skills to new situations that can extend the research potential of an exemplar. (Yan et al. 2021, 9605)

In a similar vein, Shan advocates expanding Kuhn's concept of exemplar by focusing on its non-theoretical aspect, i.e., the act of defining research problems. Kuhn originally introduced exemplars as "concrete problem-solutions" that "show [scientists] by example how their job is to be done" (1970, p. 187). Shan (2020, pp. 389–90) thinks Kuhn's characterization insufficiently captures the richness of his concept of exemplar because it draws attention to exemplars as concrete problem solutions and downplays the importance of defining research problems. For Shan, defining research problems involves various elements, such as vocabulary, practical guides, hypotheses, and patterns of reasoning (p. 392). Thus, Kuhn's concept of exemplar is expanded as a set of problems and their solutions, which contains vocabulary, practical guides, hypotheses, and patterns of reasoning.

By integrating Rouse's and Shan's Kuhnian concept of exemplar, we can define exemplar as community-endorsed ways of defining research problems, applying concepts, procedures, tools and techniques, and reasoning patterns to particular situations, and recognizing opportunities to extend these exemplary ways to new situations.
Yan et al. (2021) integrated the above two ways of expanding Kuhn's concept of exemplar and. proposed an exemplar-based hypothesis[2] for future investigation of the relationship between RA-11 and the subsequent research patterns:

> An exemplar was established by the task force that published RA-11, and RA-11 bears the identified relationship to the changes of the HRV field because it plays the role of an exemplar for the field. (Yan, Tsai, and Huang 2021, 9606)

However, as our HRV case study obtained via SciHPS shows, the tool-afforded aspects of choosing measurement methods are crucial for the entrenchment of HRV standardization. Thus, we suggest revising Yan et al.'s exemplar-based hypothesis to capture the tool-afforded aspects explicitly. We propose to use the notion of citation-exemplar to highlight the community-endorsed aspect of the original concept of exemplar.

Citation-exemplar means an exemplar identified via citation relations and practices. In other words, one needs to trace and analyze the citation relations and practices to empirically identify and characterize what an exemplar is for a given body of literature. By analyzing the citation

[2] It is worth noting that Yan et al. (2021, 9607-9608) also proposed a "repertoire-based hypothesis" for future investigation, which is based on Ankeny and Leonelli's (2016) concept of research repertoire. The repertoire-based hypothesis focuses more on the performative, social, financial, and organizational conditions in which a certain style of performing research is established, evolves, and reproduces (Ankeny and Leonelli 2016, 21).

relations and practices, one can discover which article is cited the most and why other articles cite this highly cited article. The detailed information regarding how and why an article cites another article provides a finer-grained description of how and why an exemplar is formed and entrenched.

Moreover, the citation-exemplar has more substantial descriptive power than the expanded Kuhnian concepts of exemplar because it can empirically capture the epistemic, temporal, and social aspects of scientific practice and changes simultaneously. Citation relations are social and temporal relations; they indicate how scholarly works connect and change over time. One can even look into articles' funding and affiliation information to obtain information regarding institutional and professional relations. Citation practices, on the other hand, reveal how and why the two articles are connected. By looking into how an article cites another article, one can often find the citing reason(s) in the contents of the citing or cited article.

Here we define citation-exemplar as follows:

> A citation-exemplar is an article A (or a set of articles) that is highly cited by subsequent articles within a given body of literature. The subsequent articles cite A for following A's ways of (1) defining research problems, (2) standardized procedures and measures, (3) epistemic judgments, (4) reasoning in particular situations, or (5) recognizing opportunities to extend the above ways to new situations.

We then define the citation-exemplar hypothesis of RA-11 as follows:

> RA-11 bears the identified relationship to the changes in HRV research patterns because RA-11 plays the role of citation-exemplar. Many HRV articles cite RA-11 for how it defines research problems, standardizes procedures and measures, judges which methods to be preferred for what reasons, and recognizes the opportunities to extend to non-clinical applications such as stress, exercise, and sleep.

Of course, our citation-exemplar hypothesis of RA-11 is empirical and requires more empirical evidence to test and revise iteratively. Nevertheless, we have shown that our concept of citation-exemplar and citation exemplar hypothesis of RA-11 can capture the social, epistemic, and temporal aspects of how an exemplar is formed and entrenched through citation relations and practices in a biomedical community. It is important to clarify that our goal in this section is not to argue that either the Kuhnian concept of exemplar or our proposed concept of citation exemplar is the best way to understand the entrenched biomedical standardization in our HRV case. In this section, we aim to show that SciHPS can generate a good empirical basis for testing and revising philosophical concepts that are questioned for their applicability to biomedical sciences.

5. Toward a Scientometric Approach to the Integrated History and Philosophy of Science

We extended Yan et al.'s (2021) HRV case study by investigating the methodological aspect of the HRV community. We have argued that RA-11's standardization alone is insufficient to account for the robust dominance of FDMs before and after RA-11 was published in 1996.

According to our narrative analysis of the contents of RA-11, RA-11's standardization of FDMs is tool-afforded by the FFT algorithm. On the one hand, these tool-afforded aspects reflect the community consensus during that period. This consensus can further explain the dominance of FDMs before RA-11 was published. On the other hand, because RA-11 has an excerpt group status in the HRV community, this social-epistemic status explains why RA-11 is cited 6460 times and how it entrenched the tool-afforded HRV standardizations.

SciHPS generates the above empirical case study. We then used this case study to show how SciHPS can help empirically test and revise a philosophical concept questioned for its applicability to biomedical sciences. Using Kuhnian concept of exemplar as an example, we showed how to revise this concept to the concept of citation exemplar based on our HRV case study.

As Yan et al.'s (2021 & 2022) and our HRV case study have shown, methods such as citation analysis and various text-analysis techniques can all be used to process large-scale biomedical literature and generate some robust descriptions and understandings of a body of biomedical literature. Furthermore, we have also illustrated how the scientometric approach can be used to empirically examine, modify, and defend a philosophical conceptual tool such as the Kuhnian exemplar. The novelty of SciHPS lies in amalgamating philosophical conceptual tools with scientometric tools to form an integrated method and applicable procedure for empirically investigating biomedical databases. Just as there are streamlined procedures for conducting meta-analysis in biomedical research (Moher, Liberati, Tetzlaff, and Altman 2009; Liberati, Altman, Tetzlaff, et al. 2009), SciHPS has the potential to develop streamlined procedures for HPS scholars. It can help philosophers overcome the conceptual and methodological limitations mentioned above.

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