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On the importance of investigating CME complexity evolution during interplanetary propagation

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This perspective paper brings to light the need for comprehensive studies on the evolution of interplanetary coronal mass ejection (ICME) complexity during propagation. To date, few studies of ICME complexity exist. Here, we define ICME complexity and associated changes in complexity, describe recent works and their limitations, and outline key science questions that need to be tackled. Fundamental research on ICME complexity changes from the solar corona to 1 AU and beyond is critical to our physical understanding of the evolution and interaction of transients in the inner heliosphere. Furthermore, a comprehensive understanding of such changes is required to understand the space weather impact of ICMEs at different heliospheric locations and to improve on predictive space weather models.

KEYWORDS

CME, heliosphere, magnetic ejecta, flux rope, Sun

1 Introduction and early studies

This paper [which is based on a white paper submitted to the Decadal Survey for Solar and Space Physics 2024–2033 (Winslow et al., 2022)] addresses the need to investigate, from a fundamental physics perspective, the interplanetary evolution of coronal mass ejections (CMEs), and specifically the evolution of their complexity in the inner heliosphere. The absolute complexity of an interplanetary CME (ICME) at any one heliocentric distance is difficult to define in isolation because it needs to be defined relative to a reference state of assumed low complexity (e.g., Jones et al., 2020). Generally speaking, however, complexity can be understood as the degree of similarity or deviation of a given ICME structure from a "standard" configuration characterized by a magnetic ejecta (ME) or magnetic cloud (MC) with a flux-rope magnetic structure connected back to the Sun by two "legs" (see, e.g., **Figure 2** in Zurbuchen and Richardson, 2006). Such a picture, developed through decades of observations and the consideration of a large number of events (e.g., Burlaga et al., 1981; Zurbuchen and Richardson, 2006; Kilpua et al., 2017; Luhmann et al., 2020), presupposes the existence of a paradigm accepted by the community as a descriptor of a typical, or low complexity, state.

On the other hand, it is much simpler to determine the relative change in a particular ICME's complexity between different heliocentric distances. By ICME complexity changes, we mean any significant changes in the different parts of the ICME structure (sheath/ME) both from a magnetic configuration and plasma characteristics/composition standpoint, that take the ICME from a simple (complex) starting point at one heliocentric distance to be more complex (simple) at a farther heliocentric distance (e.g., **Figure 1**).

Based on recent papers described in detail below (Richardson and Cane, 2010; Winslow et al., 2016; Winslow et al., 2021a; Winslow et al., 2021b; Scolini et al., 2021; Scolini et al., 2022a; Scolini et al., 2022b), the hypothesis exists that the complexity of ICMEs increases during propagation in the inner heliosphere mainly due to interaction with large-scale solar wind structures. The assumption is that this would occur regardless of the initial CME complexity state in the corona, i.e., some CMEs will be more complex than others at the time of initiation, however, their individual complexity state is generally expected to be lowest after launch from the Sun and increase during propagation primarily due to interactions with other transients and large-scale solar wind structures. Thus far, only a few studies, have addressed this hypothesis directly, largely due to the lack of suitable and comprehensive *in situ* data of the same ICMEs at multiple heliocentric distances.

However, currently, it is not a certainty that ICME complexity increases with increasing distance. For instance, it may be the case that a CME is formed with a relatively complex internal structure that evolves toward a simpler configuration as it expands outwards. For example, Janvier et al. (2019) found, from superposed epoch analyses of ICMEs between 0.3 and 1 AU, that the overall magnetic field profile of ICMEs became more symmetric as they propagated farther from the Sun, indicating a relaxation mechanism possibly taking place. Furthermore, Florido-Llinas et al. (2020) showed, *via* modeling with the circular–cylindrical analytic flux rope model (Nieves-Chinchilla et al., 2016), that there are conditions under which flux ropes can expand self-similarly and even become more kink-stable during propagation. It is also possible that certain regions (or substructures) of ICMEs undergo complexity increases while other areas might decrease in complexity during propagation, possibly arising from the fact that the ICME itself might not behave as a coherent unit (Owens et al., 2017). Further work is needed to properly classify and characterize such changes in ICMEs.

Many previous studies have shown that ICME properties evolve as they propagate through the solar wind due to expansion and interaction with the solar wind and transients within it (Manchester et al., 2017). Through observational and modeling work, studies have shown that during propagation, the ICME flux rope may kink and deform (Odstrčil and Pizzo, 1999a; Manchester et al., 2004; Savani et al., 2010; Török et al., 2018), reconnection/erosion of internal ICME magnetic flux may occur (Lavraud et al., 2014; Ruffenach et al., 2015), and the ICME may also get deflected (Wang et al., 2014; Kay and Opher, 2015) and rotated (Isavnin et al., 2014). Most importantly, all of the aforementioned effects are amplified by interactions with high-speed streams (HSSs), stream interaction regions (SIRs), the heliospheric current/plasma sheet (HCS/HPS) (Odstrčil and Pizzo, 1999b; Odstrčil and Pizzo, 1999c; Lavraud and Rouillard, 2014; Rodriguez et al., 2016; Zhou and Feng, 2017; Liu et al., 2019; Davies et al., 2020; Winslow et al., 2021b; Scolini et al., 2021), as well as other ICMEs (e.g., Lugaz et al., 2017; Verbeke et al., 2022), even ones observed out to Saturn (Palmerio et al., 2021), suggesting interactions with other interplanetary structures are a critical factor in the evolution of ICME structures during propagation. Overall, these studies have detailed the types of changes that ICMEs undergo during propagation, however, they have

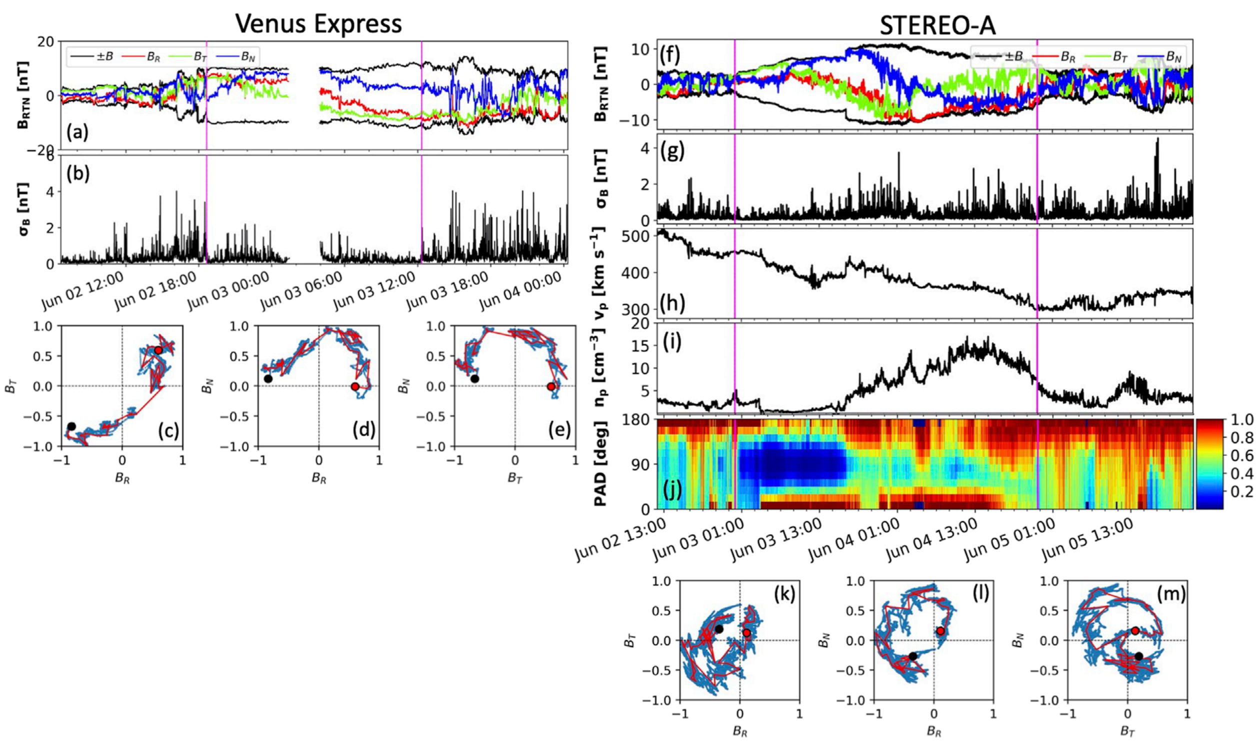

FIGURE 1
Example of an ICME observed at 0.73 au and 0.96 au in 2009 by Venus Express **(A–E)** and STEREO-A **(F–M)** in radial alignment (with a longitudinal separation of 9°). The flux-rope magnetic structure observed at the inner spacecraft **(A)** clearly appears as a more complex, non-MC structure by the time the ICME reaches the outer spacecraft **(F)** due to interaction with an interplanetary shock. From Scolini et al. (2022b), reproduced by permission of the AAS.

not considered them from the broader view of their overall complexity.

The idea that ICME structures become more and more complex with heliocentric distance has been first inferred from statistical investigations on the fraction of ICMEs that contain MC structures (Burlaga et al., 1981). At 1 AU, the fraction of non-MC ICMEs is strongly dependent on the solar cycle (Richardson and Cane, 2010), indicating that more ICMEs might have interacted with transients in the solar wind during solar maxima than during minima. Meanwhile, studies of individual ICMEs observed by multiple radially aligned spacecraft also increased our understanding of their complexity evolution. They showcased a wide variety of evolutionary behaviors, ranging from essentially self-similar (Nakwacki et al., 2011; Möstl et al., 2012; Good et al., 2015; Good et al., 2018) to strongly non-ideal (Nieves-Chinchilla et al., 2012; Winslow et al., 2016; Lugaz et al., 2020), posing questions on the frequency and causes of such a large variation in evolutionary trends.

Recent studies on ICME complexity changes (e.g., Winslow et al., 2016; Winslow et al., 2021b; Scolini et al., 2022b; Davies et al., 2022) have since uncovered many characteristics through which these changes can manifest: significant changes in flux rope structure and orientation; indications (in solar wind, magnetic field, suprathermal electron, and iron charge state data) that the ICME underwent reconnection, as well as changes in the detection of the MC substructure with heliocentric distance (e.g., if a clear MC configuration is no longer detected at spacecraft farther from the Sun although it was detected at smaller heliocentric distances). Additionally, the mass/density increase with distance in ICME-driven sheaths may affect the ME as it expands, thereby also affecting the complexity evolution (e.g., Good et al., 2020; Temmer et al., 2021). Similarly, atypical evolution of sheaths (such as significant growth beyond expected values from expansion only, as well as large increases in dynamic pressure) can also contribute to complexity changes (e.g., Winslow et al., 2021b).

It is important to note, however, that most studies of ICME complexity to date have not considered complexity changes holistically, i.e., by exploring changes in all aspects of the ICME as opposed to simply investigating one or two parameters (e.g., magnetic field configuration). Comprehensive investigations of ICME complexity are needed to test the hypothesis that complexity increases with distance, and to understand these complexity changes from a more fundamental physics standpoint.

2 Causes and effects of complexity changes

In-depth analyses of ICME case studies through multi-point spacecraft measurements in radial alignment have first illustrated the impacts that solar wind structures can have on ICMEs. Winslow et al. (2016) showcased an ICME that underwent significant deformation causing increased ICME complexity as it propagated from Mercury to 1 AU. This increased complexity was found to be due to interaction/reconnection with the HCS and HPS. More recently, Winslow et al. (2021b) presented a comparative analysis of two ICME case studies observed in radial alignment at Mercury and 1 au, of which one propagated essentially self-similarly, while the other exhibited major changes to its global structure (affecting both the flux rope and preceding sheath) due to interaction with an SIR. In a complementary study, Winslow et al. (2021a) investigated an ICME overtaken and accelerated by a HSS that was observed simultaneously by Parker Solar Probe and STEREO-A during a period of close radial alignment. In this case, the ICME interacted with the HSS for at least ~2.5 days prior to arrival at STEREO-A (i.e., the interaction began well before arrival at either spacecraft), and therefore the flux rope configuration detected in the ICME was the same at both locations. However, the ICME as a whole exhibited significant complexity (e.g., the shorter duration of the flux rope compared to the duration of the entire ME) due to the compressing action of the overtaking HSS.

The expansion of such investigations to a statistical set of events has been long complicated by the limited amount of assets capable of performing high-quality observations of ICME structures at multiple heliocentric distances. When restricting the study to only the magnetic structures of ICMEs (i.e., focusing on MEs and neglecting ICME-driven shocks and sheaths; see, e.g., ME configurations illustrated in Nieves-Chinchilla et al., 2018; Nieves-Chinchilla et al., 2019), Scolini et al. (2022b) were able to generalize previous case study results and draw statistically-valid conclusions (albeit based on small-number statistics) on the frequency, causes, and effects of ICME magnetic complexity changes. They found, from 31 ICMEs observed in radial alignment between 0.3 and 1 au, that ICMEs tend to increase their magnetic complexity with heliocentric distance, and that these changes are in most cases induced by the interaction with multiple solar wind structures, i.e., HSSs, SIRs, the HCS, or other interplanetary shocks (**Figure 2**). On the contrary, ICMEs that preserved their magnetic configuration during propagation tended to either lack any interaction with other interplanetary structures, or to interact only with a single one. An example of an ICME increasing its magnetic complexity from an inner to an outer observing spacecraft is provided in **Figure 1**. It is important to mention, however, that the Scolini et al. (2022b) study is a "trailblazer" in the sense that it is a first-of-its-kind statistical study on ICME complexity, and it is not conclusive or comprehensive. It is based on small-number statistics, the observations used lack plasma data at the inner spacecraft, and it relies on magnetohydrodynamic (MHD) model simulations of the background solar wind to identify solar wind structures that the ICME interacted with (i.e., lacks data in the propagation space). More comprehensive statistical studies are needed in the future, which can only be achieved through multiple spacecraft simultaneously probing heliospheric conditions at different distances.

Aside from alterations in the magnetic field configuration of ICMEs, Scolini et al. (2022b) also found that complexity changes are statistically correlated with reduced periods of bi-directional suprathermal electron strahls observed within ICMEs, indicative of major alterations to their magnetic topology and connectivity back to the Sun (e.g., Gosling et al., 1987; Kahler and Reames, 1991; Shodhan et al., 2000), and randomization of the average ICME internal properties such as the breaking of the speed–magnetic field relationship (e.g., Gonzalez et al., 1998; Owens and Cargill, 2002; Owens et al., 2005) that holds for unperturbed ICMEs (Scolini et al., 2022b). These results caution against the use of inner heliospheric observations to predict the magnetic field strength and orientation at a downstream target location separated by more than ~ 0.2 au.

Numerical models have allowed us to investigate the effect of solar wind interactions on ICME structures to a level of detail exceeding current observational capabilities. Of particular relevance is the possibility to include simulated spacecraft at orbits and relative positions not available in reality. Taking advantage of such flexibility, Scolini et al. (2021) quantified the probability of detecting changes in ICME complexity through a swarm of simulated spacecraft placed in perfect radial alignment between 0.1 and 1.6 au within global heliospheric simulations, given the absence/presence of corotating solar wind structures. Results of this study suggest that HSSs and SIRs dominate contributions to ICME magnetic complexity increases throughout the inner heliosphere.

We underline that such numerical investigations have been performed using global heliospheric models in simplified numerical set-ups, which facilitate the interpretation of propagation effects on different ICME regions. Future studies should address more realistic numerical set-ups and investigations of real ICME events, including comparisons with observations, as well as the use of more sophisticated models (see recommendations in **Section 4**).

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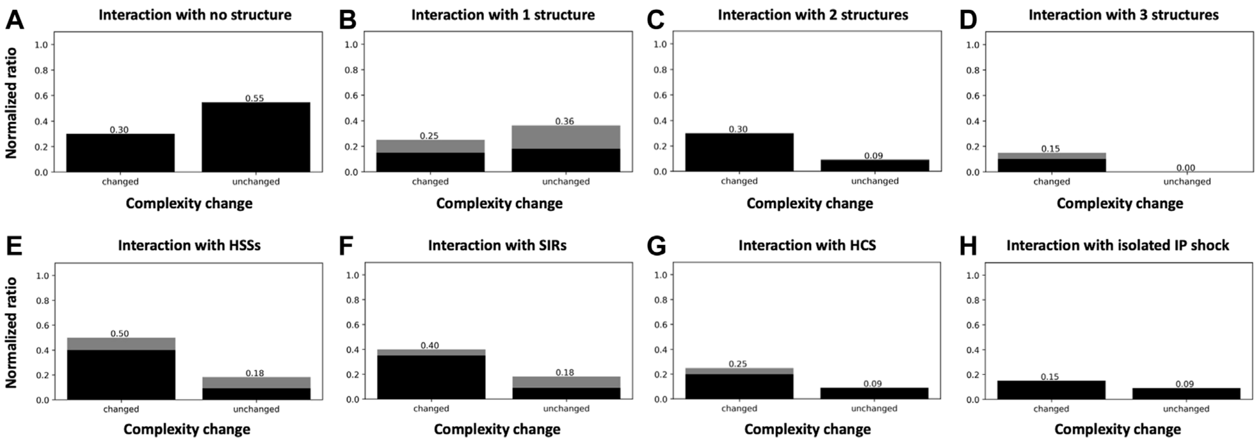

FIGURE 2
Summary of the frequency of ICME magnetic complexity changes as a function of the number of interactions that the ICME underwent during propagation **(A–D)**, and of the type of interacting solar wind structure **(E–H)**. Certain and probable interactions are indicated in black and gray, respectively. Adapted from Scolini et al. (2022b), reproduced by permission of the AAS.

3 Observational gaps: Data products and spacecraft location

When considering observational gaps, we must first consider the kind of measurements available at different spacecraft various locations in the inner heliosphere. Measurements of key solar wind plasma properties, including bulk thermal properties, suprathermal populations, and composition data are of utmost importance to decipher the fundamental nature of ICME complexity changes. By observational gaps, we mean a lack of spacecraft measurements (all or just some types) along the specific radial, longitudinal, and latitudinal locations of interest. Currently, the largest obstacle to advancing our studies of ICME complexity evolution is the lack of a full suite of *in situ* plasma and magnetic field data at small enough spatial separations but also covering a large distance range (and therefore likely needing to involve a large number of spacecraft) from the Sun to 1 au to unambiguously detect complexity changes and determine their causes.

In general, gaps in the aforementioned data products available may: 1) lead to higher uncertainties in the identification of ICME boundaries (e.g., Cane and Richardson, 2003; Riley et al., 2004; Jian et al., 2006; Al-Haddad et al., 2013; Winslow et al., 2015; Good and Forsyth, 2016; Davies et al., 2021); 2) prevent a detailed investigation of the physical phenomena (e.g., magnetic reconnection, forces, conversion/transfer of energy between ICME substructures, generation/propagation of plasma waves—see Manchester et al., 2017 for reference) involved in complexity changes observed within ICMEs (e.g., Winslow et al., 2016; Farrugia et al., 2020); 3) complicate the interpretation of ICME kinematics/propagation (e.g., Hess and Zhang, 2014; Lugaz et al., 2020); 4) complicate the identification of large-scale structures interacting with ICMEs (e.g., Scolini et al., 2021); 5) complicate the identification of complexity changes that may have occurred due to the lack of the same type of observations at multiple spacecraft locations (e.g., Scolini et al., 2022b).

Unfortunately, the limited number of spacecraft able to cross individual ICME structures (Lugaz et al., 2018) has prevented the spatial (i.e., longitudinal and latitudinal) characterization of the magnetic complexity distribution within MEs and their radial evolution or temporal changes. This is true both near 1 au, where a maximum of three spacecraft crossing individual ICME structures along different radial directions has been achieved only in the early phases of the STEREO mission at solar minimum (Farrugia et al., 2011; Kilpua et al., 2011; Ruffenach et al., 2012), and also in the inner and outer heliosphere, where measurements are typically rare and single-spacecraft based. Exploiting the ability to simulate spacecraft swarms in global heliospheric simulations, an exploratory numerical investigation by Scolini et al. (2022a) estimated the minimum number of spacecraft that would be required to characterize the spatial distribution of magnetic complexity within MEs and its evolution with heliocentric distance, depending on the ICME propagation scenario (i.e., whether there were interactions with other large-scale solar wind structures). The study revealed that ICME magnetic complexity requires a minimum of ∼10 spacecraft crossings at every 25° to be fully characterized globally. With less spacecraft crossings available, the complexity determined based on *in situ* data may not be indicative of the actual complexity of the ICME structure as a whole. Interactions with other large-scale solar wind structures such as SIRs and HSSs are also found to increase the minimum number of spacecraft crossings required by a factor of 4–10, bringing it up to a minimum of 50–65 spacecraft at a minimum of 10° of angular separation.

The simulations by Scolini et al. (2022a) also suggest that ICMEs may retain a lower complexity level along their magnetic axis. In this respect, future missions composed of spacecraft swarms orbiting in the ecliptic plane may characterize the complexity evolution of low-inclination ICME flux ropes (i.e., having their magnetic axes approximately aligned with the ecliptic plane; Kilpua et al., 2017) near the ecliptic plane with as little as ∼6 spacecraft crossings, rising to ∼9 in case of interaction with HSSs and SIRs. More such numerical studies are needed to inform preparations for future spacecraft missions to optimize necessary observations and allow for significant progress to be made in this field.

4 Open questions and suggestions for the community

As described above, although a number of recent studies have investigated complexity changes in ICMEs with multi-spacecraft measurements and simulations, many open questions remain. It is important to highlight that most studies on this topic so far have addressed magnetic complexity changes only, not viewing ICME complexity from a holistic standpoint (i.e., looking at both large-scale magnetic configuration changes as well as changes in the plasma characteristics and composition). A holistic view is necessary, however, in order to fully test the hypothesis that ICME complexity generally increases with increasing heliocentric distance. The main limitation to such comprehensive studies is the lack of plasma and magnetic field measurements of the same ICMEs at various radial and longitudinal locations in the inner heliosphere.

Compelling open questions in this area, from a fundamental science perspective, are:

- In general, does the overall complexity of individual ICMEs (including magnetic configuration and plasma characteristics in the different ICME substructures) increase with heliocentric distance in the inner heliosphere? Or is it more common for the ICME internal structure to simplify as it evolves (through Taylor relaxation for example)? Alternatively, is it more likely that different ICME substructures behave differently from each other, i.e., ICME complexity increases in some parts while it decreases in others? Furthermore, does the trend in complexity evolution change as the ICME propagates?
- What are all possible drivers of ICME complexity changes during propagation? Also, what is the main driver?
- To what extent are ICMEs coherent and how does this affect their complexity evolution?
- How do instabilities/small-scale processes contribute to global ICME complexity changes?
- To what degree, if at all, does the presence of a shock/sheath protect the ICME ME from large-scale and comprehensive complexity changes?
- How does ICME–ICME interaction affect the individual ICME's complexity?
- How do ICMEs of different complexity levels affect the global heliospheric magnetic field and contribute to the heliospheric flux budget?
- Can we leverage proxy observations to gain information about ICME complexity?

Here, we suggest the following ideas to the community to tackle together these compelling open questions:

1) More comprehensive *in situ* ICME measurements are needed from the Sun to 1 au at multiple heliocentric distances and angular separations. This would entail having magnetic field, solar wind plasma, and suprathermal electron measurements at many locations radially outwards from the Sun. The current standard time resolution of magnetometers and plasma and electron spectrometers at a continuous duty cycle should be sufficient for these studies. Initially, we recommend pathfinder mission(s) combined with simulations allowing for the exploration of the parameter space, while for the following decades, a dedicated flagship mission building on these findings would be necessary to substantially advance our understanding of ICME evolution.
2) Options should be explored on the optimal spacecraft configuration in terms of radial, longitudinal, and latitudinal spacing through simulations to achieve the necessary spatial resolution in the data needed to fully explore ICME complexity evolution in the inner heliosphere.
3) Once the data are available, more comprehensive/holistic studies of ICME complexity evolution are needed, integrating the results from many vantage points.

Exploratory investigations using global heliospheric simulations are already showing us how spacecraft swarms can be best used to investigate the physical origin, evolution, and spatial distribution of magnetic complexity within ICMEs. In the future, we stress that simulations need to be able to resolve more physics (e.g., achieving more accurate characterizations of small-scale phenomena such as magnetic reconnection and shock–ICME interactions), and be able to include more realistic descriptions of the global internal magnetic configuration of MEs, including alterations arising from their early evolution in the solar corona, in order to test such numerical simulations against real ICME events.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Author contributions

RW and CS wrote the majority of the manuscript, with input from all other co-authors. All authors provided input and comments on the manuscript.

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Conflict of interest

Authors EP and TT were employed by Predictive Science Inc.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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