Canonical Workflow for Experimental Research (Postprint)

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Abstract

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Full Text

Preamble

Canonical Workflow for Experimental Research

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ABSTRACT

The overall expectation of introducing Canonical Workflow for Experimental Research (CWFR) and FAIR digital objects (FDOs) can be summarised as reducing the gap between workflow technology and research practices to make experimental work more efficient and improve FAIRness without adding administrative load on researchers. In this document, we describe, with the help of an example, how CWFR could work in detail and improve research procedures. We have chosen the example of "experiments with human subjects" which stretches from planning an experiment to storing the collected data in a repository. While we focus on experiments with human subjects, we are convinced that CWFR can be applied to many other data generation processes based on experiments. The main challenge is to identify repeating patterns in existing research practices that can be abstracted to create CWFR. In this document, we include detailed examples from different disciplines to demonstrate that CWFR can be implemented without violating specific disciplinary or methodological requirements. We do not claim to be comprehensive in all aspects, since these examples are meant to prove the concept of CWFR.

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1. INTRODUCTION

Research based on experiments in controlled environments is one of the fundamental scientific paradigms for gaining new insights. In this paper, we focus on

experimental research with human subjects in areas such as psycholinguistics, psychology, economics, social sciences, medicine, and related research domains. Within a large German funding program, experts from these areas came together to discuss the characteristics of their experimental processes in detail, with the goal of identifying commonalities and creating a shared perspective on improving FAIRness [1]. The key observations from this discussion confirmed findings from a comprehensive analysis of many research infrastructure projects [2].

There are only marginal differences when a specific experimental paradigm (e.g., randomized controlled trials, game theory experiments measuring behaviour, factorial surveys measuring attitudes) is used across disciplines, but substantial differences exist (e.g., in ontologies, metadata, and processing) between different methodological procedures. Importantly, it is not the domains and disciplines (e.g., Sociology) but the methodological paradigms (survey experiments, psychological experiments in the laboratory or field, behavioral game theory experiments in the laboratory, field, or online) that yield the specifics, such as finding appropriate ontologies and metadata to describe and document the experiment. For example, all behavioral game theory experiments can be described within the same metadata schema, regardless of whether they were conducted in Sociology, Political Science, or Economics.

The FAIR principles were known to all experts; however, actual research practices hardly changed to implement these principles for the majority of studies, often due to relatively small monetary resources and/or communities lacking adequate research data infrastructures and best practices. One reason for this procedural inertia might be that extensive adaptations of various tools would be necessary to realize a general implementation of the FAIR principles into existing research workflows. At the same time, limited developer capacities and the constant need for prioritized methodological features restrict resources for these adaptations.

There are many repetitive steps in daily work, starting with experiment preparation through to data analysis, yet no workflow mechanisms are in place to cover these repetitions and allow researchers to benefit from more efficient processes. The expert group agreed that (1) major steps and investments would be necessary to change the situation toward greater efficiency and FAIRness, (2) a joint approach across disciplines and methodological paradigms would be reasonable given the similarity of workflows, and (3) practices are required that take the load off researchers to create the necessary motivation to comply with these workflows. This agreement was made with full consciousness that adaptations of existing solutions may be expensive and, in some cases, even impossible. Since in most experimental labs specific sequences of actions need to be taken repeatedly, implementing canonical workflows consisting of harmonised components without adding load on researchers seems a promising approach.

We use the term “lab”in a broad sense for all kinds of data-generating, managing, and processing environments, including field and online experiments. A widely

accepted solution for low-effort documentation is to immediately create FAIR Digital Objects (FDOs) [3, 4] at each workflow step. FDOs "bind all critical information about an entity in one place and create a new kind of actionable, meaningful and technology independent object." This approach would also allow embedding existing tools. Initially, wrappers could be used to integrate these tools where possible until the tools themselves are changed to support FDOs.

The overall expectation of introducing CWFR and FDOs can be summarised as reducing the gap between workflow technology and research practices to make research processes based on experiments more efficient, improving FAIRness without adding administrative load on researchers through, for example, automatically generated metadata and archiving of digital objects.

In the following section, we present nine distinct and atomic steps that can be identified as sufficiently similar in experiments with human subjects across disciplines. Some steps can be skipped when implementing the workflow if they are not required by institutional or legal regulations.

We do not consider data analysis from experiments an integral part of the basic experiment CWFR for two reasons. First, the process of analysing data is considerably more complex than all other steps within the workflow and would create a bottleneck when identifying similarities. Second, data analysis is typically much more differentiated across disciplines and woven much deeper into well-established practices. Including this step would likely hamper any harmonisation attempt. We are, however, convinced that data analysis with a different sequence of steps requiring different strategies and components could be turned into a separate canonical workflow. It should also be noted that despite all harmonisations in many experimental paradigms that suggest using a workflow framework, there will always be studies requiring specific developments and a particular set of actions.

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2. A COMMON EXPERIMENTAL WORKFLOW PATTERN

In Figure 1 [Figure 1: see original paper] we present the canonical experiment workflow consisting of nine atomic steps that cover the typical process of a research project based on a controlled experiment. The preparation phase includes five steps and starts with discussing intentions and expectations. This needs to result in a hypothesis formulated in some form dependent on the lab environment. In well-organised labs, this will be described in the form of a short document. Following this step, a suitable experimental design will be chosen, which is largely a prose text that may include references to experimental paradigms often used for classes of experiments in different disciplines and sometimes references to experiment execution software suitable for carrying out the work. After iterations, this step will result in a short document.

The next step includes specifying detailed experimental parameters such as type and set of stimuli to be presented, concrete actions to be taken during experiment execution, timing of actions, and types and number of subjects to be included to achieve reliable results. To select stimuli and subjects, this step often includes using specific databases, software, and tools that contain preprogrammed stimuli or the participant pool. Each lab has its own way of organising and structuring this data and thus uses specific databases and tools, and access to the subject database might be restricted to protect personal data. Also, the list of parameters to be specified depends on the experimental software being used, which suggests using formal key-value pairs in the specification document so that later transformers can be easily built. To select stimuli and subjects, it may be necessary to split this step into a short sequence of steps, each associated with a specific software component.

In many research fields and institutions, it is required to ask for an ethics review by an institutional review board. While formats differ across institutions, the set of information to be provided can mostly be generated from already created descriptions—i.e., if information from the first step is structured, it is possible to create ethical requests with simple transformers. In some domains, simplified ethics reviews have been realized and could lead to an actionable ethics review request management tool. In some cases, researchers preregister their experiments, which can also be generated based on already entered information. It should be noted that in the case of ethics review in the medical field, automation is hardly possible due to legal regulations, but the "Gesellschaft für experimentelle Wirtschaftsforschung (GfeW)" has already set up a simplified ethics review process that appears to be automatable. The Erfurt Lab is also currently pushing ahead with development of a (partially) automated ethics review.

The ethical review can raise concerns that may lead to revision of the experimental setup or some components. In other cases, results of a pre-test might create the necessity to readjust some experimental parameters. When the ethical request is positively reviewed and tests are positive, the actual experiment can begin. It needs to be mentioned that special software is generally used to support tests and experiment execution. The rationale is that these experiment programs are highly specialised since specific hardware needs to be interfaced, tight timing constraints must be respected, and particular action sequences must be implemented. This implies that a wrapper needs to be developed that extracts all needed parameters from existing data structures, transforms them into required structures, and submits them as attributes in the call to start the experiment software. Often stimuli are presented as lists in a separate file, meaning one of the attributes will be a reference to a list.

Experimental actions are generally repeated over M items and N subjects, i.e., a micro-workflow embedded in the experiment software is repeated N*M times, which includes some measurements. Therefore, the result file generally includes N*M vectors with all relevant information necessary for analysis. Experiments

with many subjects, however, are not executed in one run. Often these experiments are stretched over long periods, and in some cases the same subjects are tested again after some time, e.g., for longitudinal experimental studies. In such situations, the collected data needs to be integrated into one dataset ready for analysis. Such datasets are then stored and registered. To prevent data loss or accidental exclusion of sessions, different measures need to be taken which could also help prevent "fraud." Backup copies of each session will be necessary but not sufficient as long as hashing of content is not incorporated, as suggested by using FDOs.

As shown in Figure 1, the canonical workflow framework will help researchers create proper documentation from the beginning, which will then be extended at each step so that at the end a comprehensive metadata description is ready without retyping information. This functionality is often part of virtual research environments (VRE) designed and configured to facilitate typical tasks related to project administration and research data management.

In these workflows, some specificities need attention.

Revision. In some steps, revisions within the action may occur. If they are not implemented by "micro-workflows" within specific software, the canonical workflow needs facilities to handle these revisions. As an example, we could refer to tests that might have to be done several times with parameter adjustments, which generally require human interaction.

Non-Linearities, Splitting, and Merging. At each step, researchers must be able to go back to a previous step and start with previously made descriptions by adapting them, i.e., no retyping is required. This implies that at any step a Digital Object must be created that contains all information and points to other information, e.g., referring to prior FDOs containing former versions.

Researchers might also want to start some steps in parallel; for example, after experimental design they immediately want to start the ethical request procedure. Parallel actions will be started and finished asynchronously. In addition, a timer may be started to remind researchers to check the state of the ethical review process. Facilities need to be provided to merge these different paths again.

Researchers often conduct more than one experiment at a time to test various experimental settings, i.e., parallelism needs to be taken care of at the project level in addition to parallelism within the workflow. Every project runs its own instance of the framework.

Interoperability. CWFR is an excellent vehicle to substantially improve FAIRness and thus interoperability of produced data. Currently, most data is exchanged without any further metadata associated with it, resulting in the well-known 80% loss in efficiency since data receivers need to find out what the data is about and how it can be interpreted. CWFR has the chance to make metadata creation as easy as possible for researchers since it will guide them from the

beginning of experiments and allow them to stepwise add information through automatic measures such as extracting header information from recordings. In addition, by introducing FDOs as underlying mechanisms, the strong relation between PID, data, and metadata (of different sorts) will not be lost over time. It is the strength of FDOs to keep the binding between all relevant information as long as needed. CWFR based on FDO technology is the way to introduce FAIR compliance and increase interoperability without adding additional load on researchers.

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3. FINAL CANONICAL WORKFLOW AND VIRTUAL RESEARCH ENVIRONMENTS

Concerning workflows as sketched above, two major phases can be distinguished:

- **Phase 1** is characterised by specifying the sequence of actions to be carried out and the type of data/metadata needed.
- **Phase 2** is characterised by executing such a specified sequence of actions.

As already indicated, in this paper we will not discuss the analysis phase since different characteristics and types of processes are involved. We will also not discuss interactive workflow frameworks separately, since the specification and execution steps are combined in one framework associated with asynchronous processes.

3.1 Preparation Phase

The experimental project begins with creating a first empty metadata FDO called Exp_{MD}_{FDO}. A simple editor can add descriptions of intentions, hypotheses, and usual entries such as researcher name, experiment name, date, etc., to this FDO. For later extraction purposes, it would be helpful to structure the input using agreed keywords. The next step using an editor is to describe the experiment design, which is a more prose-like description that can be used, for example, for ethical review, in publications, etc.

At an early stage, researchers request ethical permission to carry out the intended experiment. If necessary, an ethical request is packaged from already specified information in Exp_{MD}*{FDO} and sent to the corresponding board by email. In cases with structured information in Exp*{MD}_{FDO}, this process of mapping information to given templates can be automated.

In parallel, researchers start defining experiment parameters, which is highly dependent on the experimental paradigm and chosen software. To optimally support users, it would be useful to start an editor and invoke a template associated with the software and paradigm being used. As indicated above, this step may involve actions widely taken care of by the experimenter.

The set of micro-actions in the experiment needs to be defined and their timing specified; the set of stimuli per micro-action needs to be selected and probably ordered; and the set of subjects that will participate in the experiment will be selected, which mostly involves email interaction and many adjustments.

Special software is typically used to access the pool of stimuli (acoustic, visual, etc.) and make selection as efficient as possible. The design informs how many such stimuli targets are required and which characteristics they need. This selection results in an ordered list of values and/or paths to files that can be used by experiment execution software.

Also, special software is typically used to access the subject database and select appropriate subjects needed for a specific experiment. A list of possible candidates is prepared, much interaction is needed to check availability and suitable dates, and finally subjects are requested to participate at certain dates and times. Often subjects are identified by specific codes only known to a responsible subject pool manager, and these codes are then transferred to execution software to include them in result files.

In this paper, we assume both lists—stimuli and subjects—are stored as DOs for documentation purposes, and that Exp_{MD}*{FDO} will include the PIDs of these two FDOs, which we call Exp*{Stim}*{FDO} and Exp*{Subj}_{DO}. There is no doubt that suitable tools need to be available to make these transitions as simple as possible for researchers. Storing them as FDOs and DOs will also allow experimenters to reuse them for other purposes over time with small changes, i.e., the time-consuming selection process can be reduced.

As medicine is one of the most regulated areas, it might serve as a stress test at this workflow step for Exp_{Subj}_{DOs}, adhering to applicable quality guidelines/standards: GCP—Good Clinical Practice Guide Requirements for electronic trial data handling systems; GAMP 5 Guide: Compliant GxP Computerized Systems Computerized system validation of GxP systems; ISO 13485: 2016—Medical devices—Requirements for regulatory purposes.

After the ethical permit has been received, some experimenters like to register the experiment to document it. If the registration site has an API, this step is also reduced to simple automatic interaction where needed information is extracted from Exp_{MD}_{FDO}. Any repository that supports DOIP can be used to store FDOs. As always, it will be up to implementations to generate indexes, etc., to support fast actions.

3.2 Test and Execution Phase

After all preparations, tests can be carried out to ensure that the experimental paradigm and chosen parameters together with hardware and software setup guarantee smooth experimentation as expected. Often these tests result in changing specific parameters and the list of stimuli, i.e., testing mostly results in iteration cycles to redefine the experimental setup. Sometimes even the exper-

imental design and hypothesis need adaptation, which would require restarting workflow steps. This would result in a new Exp_{MD}_{FDO} object instantiated based on the old one depending on the repeated step, i.e., researchers only need to enter changes.

To carry out tests, selected experimental software needs to be executed, i.e., a wrapper must be called receiving the Exp_{MD}*{FDO} object which includes all necessary information or references to needed information. The wrapper will then transform existing information so experimental software receives interpretable input. It would be helpful if information in Exp*{MD}_{FDO} is structured and can be interpreted by machines, which requires defined semantics registered in an open type registry—a specific type of semantic artifact such as provided by GWDG.

At the end of test runs, experimental software returns control to the wrapper which creates an FDO called Exp_{Res}*{FDO} containing usual metadata and a reference to the structured result file. This can be visualised with means used by researchers. When tests are unsatisfactory, going back to earlier steps is required as indicated above. When they are positive, Exp*{MD}*{FDO} will be extended by a reference to Exp*{Res}*{FDO} to document successful testing, and execution software can be started again—now with all information (stimuli, subjects, parameters) for the real experiment. The result will be a new Exp*{Res}*{FDO} containing all results in structured form, and Exp*{MD}*{FDO} will be updated to include the PID of the new Exp*{Res}_{FDO}.

3.3 Orchestration and Virtual Research Environment

Virtual Research Environments (VRE) (Candela et al., 2013) are designed to optimally support researchers in conducting research while supporting orchestration and ensuring produced data are managed according to RDM best practices (including FAIR Data Principles). During orchestration, the sequence of steps needs to be specified. We assume availability of components that can be chosen in a component software library, i.e., for each step indicated in the workflow as shown in Figure 3 [Figure 3: see original paper], and perhaps even more that have not yet been identified.

During orchestration, researchers select useful components from a library that can help move to the next state. The library will be organised offering canonical steps and specialised packages. After each step, a processing stateX is documented comprehensively by Exp_{MD}*{FDO}, i.e., all chosen steps are described in a workflow process file (WPF) adhering to standard formats agreed upon by the broad workflow community and referred to from Exp*{MD}_{FDO}. WPF typically includes the sequence of steps and for each step a structure that can be used during execution to add process information.

At stateX, the VRE supporting orchestration will allow users to select software components to launch to reach the next stateX+1. Generally, this happens in two actions to make it easy for researchers: first a step is chosen, then a

specific software package addressing needs is selected. In the case of experiment execution, even more filtering might be necessary to select the right software supporting the chosen paradigm.

We assume different specialised libraries will emerge to support different research disciplines. We also assume wrappers will be available where necessary to embed existing software packages. The glue binding the workflow together is Exp_{MD}_{FDO}. At each stage, it is updated to include all relevant workflow process information. We assume either integrated software packages or wrappers embedding packages support the Digital Object Interface Protocol (DOIP) and interact with a repository that can also talk DOIP independent of its local data organisation.

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4. CONCRETE EXAMPLES

Specially created micro-workflows will be used to actually run tests and experiments using specific software packages. Many have been developed to meet specific requirements, often with hard timing constraints. A large variety of experimental paradigms are used in various experimental labs. Here we refer to examples that may indicate differences.

4.1 Psycholinguistics

Often experiments are carried out to understand pre-activation of a cohort of concepts when a certain target concept is presented to a human subject (visually, acoustically). "Concepts" stored in the human mind are typically represented by activation patterns of neuron sets, triggered by signals issued when other (semantically) related concepts are recognised. The assumption is that when a specific item is shown to a human subject, it will pre-activate other items in the mind, with the result that if such a related item is presented, subjects respond faster.

The Micro-Workflow would typically look like:

1. A stimulus is presented to the subject.
2. The subject is asked to name the stimulus.
3. At speech onset, the timer stops, yielding reaction time.
4. A record with all experimental parameters (image numbers, timing parameters, subject number, reaction time) is added to a file.
5. Finally, the experimental result file is stored safely.

The following aspects should be noted: There are different variants of such experimental paradigms, i.e., reactions can be measured differently, time-series data (eye-tracking, brain imaging, etc.) could be measured in parallel to detect mental activity during stimulus processing, etc.

Often special tools are used to implement such Micro-Workflows to meet narrow timing constraints. This implies that the CWFR shown in Figure 2 [Figure 2: see original paper] needs to embed such micro-workflows at the "run tests" and "execute experiment" steps. It will be crucial to find a way to interface between the CWFR part and Micro-Workflows since different tools are used. Often these tools cannot be changed easily, i.e., they should not be loaded with the need to use or create digital objects. This should be done by the CWFR wrapper.

4.2 Experimental Economics

A large share of behavioural (economic) experiments are conducted in computerized laboratories, i.e., participants are placed in front of computers where they receive information about the decision context. Participants are informed about available choices and consequences of each choice. After that, participants choose either for themselves or in interaction with others from these alternatives. Participants' behaviour or choices are usually recorded as inputs of numbers or text, or via different choice scales.

In most cases, decisions are stored anonymously, meaning personal information is not stored alongside decision data because it is hardly used in analysis. If collecting demographic information is necessary, it is also stored in anonymized or pseudonymized ways [5]. The following steps describe a typical micro-workflow found in most economic laboratory experiments:

1. Participants receive an invitation to a particular experiment via email containing information about date, time, and length.
2. Participants who show up at the laboratory are randomly seated at computers.
3. After sufficient participants arrive, the experimenter presents instructions and rules.
4. If participants interact, they are randomly allocated to groups—an important dataset variable.
5. Once all participants signal understanding, the experiment starts.
6. Many experiments are played repeatedly, i.e., participants face the same or similar situations several times. All decisions are recorded in a spreadsheet.
7. After the last decision, participants may complete an additional questionnaire describing their experience, motives, or strategies.
8. At experiment end, participants are usually paid in cash or via online transfer. Payment depends on their choices and/or others' choices. Payment data is stored in a separate spreadsheet.

The same workflow applies to online or field lab experiments. In the latter, data may also be recorded on paper and digitized later. Behavioral data collection may be complemented by physiological measures, e.g., galvanic skin resistance (GSR), eye-tracking, or electroencephalography (EEG). Software for behavioral economic experiments ranges from standardized questionnaire tools to very spe-

cific tools exclusively developed for economic experiments. For physiological measures, hardware usually comes with preconfigured software tools that vary between providers.

Tool and software package availability is primarily affected by the laboratory, usually based on demand from the most active researchers. The same is true for requirements and regulations regarding data storage and management. Consequently, many laboratories store large amounts of raw data and auxiliary materials (like instructions, program code) on local devices. Typically, data in these lakes is hardly described with metadata beyond information necessary to organize experiments (like date, time, participant number). These metadata pieces are rarely transferred to published datasets.

All micro-workflow steps described above typically happen after study design testing (Step 6 in Figure 1). Right after actual experiment conduct (Step 7 in Figure 1), anonymized data can be added to the existing FDO for the study.

4.3 Social Sciences

In social sciences such as sociology and political science, methodological paradigms in experimental research vary. For example, behavioral game theory methodology, having roots in Experimental Economics as described above and following induced value theory assumptions [6], has been adopted by other disciplines like social sciences. Researchers following this experimental paradigm use similar workflows and metadata across disciplines. Machine-readability is easy to achieve here, as the range of core metadata—for example, on experimental design and setup—is predetermined to a large extent. Consequently, tools used in game theory experiments hold a critical position for CWFR and FDOs. To fully realize CWFR potential, the MD_{FDO} describing experimental design must reflect the degree to which it meets game theory experiment standards. For example, the no-deception clause and appropriately high monetary payoff are two mandatory properties. Deviation from these standards, e.g., identical payoff levels for students and professionals, could cause misinterpretation of results.

The steps described in Figure 1 are consistent with methodological paradigms used in experiments. However, good scientific practice is guided not by particular methods but by discipline. In analytical-empirical sociology, step 5 is increasingly recommended (pre-registration) [7]. In experimental economics, according to Society for Experimental Economic Research (GfeW) standards, step 5 can be omitted if full reporting is provided as alternative.

Survey experiments, e.g., factorial surveys [8] or conjoint analyses [9], measure attitudes and behavioral intentions rather than behavior. If data reusability across methodological research paradigms is intended, these assumptions need documentation in the MD_{FDO} of data published in the final project step. Sociology also involves experiments with behavioral interventions, with methodological background in social psychology. Additionally, clinical randomized con-

trolled trials in medical sociology might include studies with "experimental" treatments compared to "control" treatments and control groups without intervention. Regardless of methodological paradigm or discipline, all experiment types follow the canonical steps described above.

4.4 Medical Domain

For medical experiments (especially randomized controlled trials, RCTs), in-depth quality assurance procedures must be installed in most work steps, and applicable quality guidelines and standards adhered to. These include GxP standards known from related fields, e.g., GCP—Good Clinical Practice Guide or GAMP 5 Guide. Requirements for electronic systems processing study data are manifold and cover workflows discussed here. However, since the entire system must always be validated and certified, workflows as part of the system (and CWFR in general, at least if implemented in advance) can generally be assessed as meeting requirements, ensuring high quality and fluidity of work. The GAMP 5 guide, like all GxP requirements, requires compliant computerized system validation—a requirement that should not have to wait much longer for legislative implementation.

Regarding law, as soon as processed data is patient data and thus Patient Health Records (PHR), the strictly regulated terrain of medical devices is quickly entered. Exemplary but not exhaustive are harmonized ISO 13485:2016 and ISO 62304:2016, defining requirements for software as a medical device (SaMD) regarding regulatory purposes and control product compliance. Interoperability requirements have also found their way into digital medicine: in addition to Medical Devices Regulation (MDR 2017/745), German standards of Sections 394 ff. of German Social Code, Book V (SGB V) also stipulate that information technology systems must be semantically, syntactically, and structurally compatible. The demanding area of data protection and security needs no mention; immense requirements should be generally known.

Beyond this brief excursion into the regulated world of medical devices, numerous recognized standards frame medical research, research software systems, and workflows. FAIR principles have also begun their triumphant march in medical research. Driven by the FAIR consortium of representatives from academia, industry, funding agencies, and scientific publishers—a growing "data science community" —existing and new data are being discovered, integrated, and analyzed. For example, at the metadata level, to develop a FAIR registry for medical data, taking into account FAIR Data Principles. Here, demand for interoperability, functioning workflows, and secondary use in research becomes clearly audible.

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5. CONCLUSIONS

Analyzing experimental practices in laboratories across different disciplines collecting behavioural data from human participants indicates that similar steps are taken in all these places—steps we can indeed call canonical in workflow scenarios. Some steps have different flavours, such as ethical review where all research organisations have their own templates. However, with some exceptions (as in medical laboratories), the same kind of information from researchers is needed across disciplines and methodological paradigms. Therefore, it makes sense to develop a CWFR-like framework across disciplines, provide libraries of packages organised by steps, and allow researchers to easily adapt canonical workflows to their specific needs that can then be executed repeatedly. These would guide them through various steps without needing to bother with details.

These workflows will need to embed existing tools, such as for selecting subjects and stimuli used in executing experiments. Different labs have developed their own tools for these steps, partly integrated with databases, which would have to be embedded by wrappers that also convert gathered parameters so external programs can use them as input. Especially experiment execution software packages are often highly specialised due to controlled hardware (special instruments), tight timing tolerances, and embedded micro-sequences of actions. Obviously, software for these tool integrations by wrappers would need development by experts.

Experiments with humans imply special features that workflow machinery must address:

- Experimental designs and parameters are usually revised at the beginning of the research process, requiring many iterations until final settings are established.
- Experimental workflow execution is highly asynchronous since at some steps researchers need to wait for external signals or apply parallelisms.
- Experiments are often executed in different labs due to access to different instruments and subject types.

These requirements and recurring patterns suggest implementing CWFR principles and basing all experiment documentation on FDOs hosted in any DOIP-adapted repository for all steps, assuming content structure has been standardised. This would remove administrative work from researchers, widely improve experimental work efficiency, create FAIR-compliant documentation of all experimental steps without bothering researchers, and make it easily possible to run experiments in different labs.

AUTHOR CONTRIBUTIONS

All authors contributed ideas, text, and review comments in producing the paper. C. Blanchi (cblanchi@cnri.reston.va.us) is a core developer of Digital Object

Architecture components and therefore a major contributor. P. Wittenburg (peter.wittenburg@mpcdf.mpg.de) is co-editor of the FAIR principles paper and member of the FDO Forum, and a major contributor to FAIR and FDO aspects.

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AUTHOR BIOGRAPHY

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Note: Figure translations are in progress. See original paper for figures.