**Research collaboration in Large Scale Research Infrastructures:
Collaboration types and policy implications**

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**Abstract**

Over the past decades, Large Scale Research Infrastructures (LSRIs) have come to play a central role in providing scientist-users access to highly specialised scientific instrumentation and experimental conditions. Collaborations between (permanent) instrument scientists and users are at the core of these organisations, yet knowledge about the nature of such collaborations and their development over time is surprisingly scarce. In particular, we know very little about the interrelation between the individual and organisational drivers of collaboration. Based on a qualitative study of scientists and their collaborations at *Institut Laue-Langevin*, a world-leading neutron source, we identify four typical collaboration patterns, which reflect particular configurations of (dis)similarity between instrument scientists and users in terms of perceived expertise gap and co-development focus. Our findings suggest that the co-existence of multiple collaboration types within the same organisation plays an important role in the long-term success of LSRIs. In addition, we contend that dissimilarity can generate productive collaboration to the same extent as partner similarity; not only at the organisational level – co-existence of different types of collaborations across the LSRI, favouring the co-existence of a broad range of instrumentation – but also at the individual level – where instrument scientists benefit in terms of more productive collaborations over time despite the cost of learning involved.

**Keywords**

Large Scale Research Infrastructures (LSRIs); research collaboration; partner (dis)similarity; collaboration pattern.

**JEL code**

O30; O32.

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**1. Introduction**

This article addresses scientific collaboration in the context of Large Scale Research Infrastructures (LSRIs). LSRIs are defined as large scientific instrumentation, facility, and equipment clusters that require large investments and complex engineering and networking efforts; they are usually recipients of funding by national or supranational bodies and shared by communities of scientists (Qiao et al., 2016). Most LSRIs can be characterised as large experimental platforms, including, for example, synchrotron radiation sources, neutron sources, or advanced laser facilities, which serve both fundamental and applied research in a wide range of scientific disciplines (Qiao et al., 2016). The purpose of experimental platforms consists primarily in providing scientist-users access to highly specialised scientific instrumentation and experimental conditions beyond the reach of most university organisations. In areas such as neutron scattering, synchrotron radiation, and free electron lasers facilities, experimental platforms require intense collaboration between permanent scientists and external users, which is essential to produce science (Hackett et al., 2004; Hallonsten, 2016b:486), and facilities need to be highly specialised while remaining attractive to broad scientific communities (Heidler and Hallonsten, 2015).

Despite their importance in science policy and practice (Lozano et al., 2014), research on LSRIs as settings for scientific collaboration is surprisingly scarce (Lauto and Valentin, 2013:383). Previous LSRI research has shed light on the historical development and science policy surrounding specific organisations (e.g., Hallonsten, 2009), their scientific performance (Hallonsten, 2013; Qiao et al., 2016), and their role as linkages between local and non-local knowledge (Lauto and Valentin, 2013). Some research has placed emphasis on how computer-supported environment can enable and facilitate collaboration in the context of shared facilities (Bos et al., 2008). Yet, the particular form of repeated collaboration in the context of LSRIs whereby scientists need to aim for both developing longer-term collaborations with users and fitting with a wide range of (potential) users' scientific interests has not been sufficiently addressed by traditional research collaboration literature. Moreover, while a large body of previous literature on research collaboration addressed collaborations involving large teams of scientists (Bozeman and Youtie, 2017), our research sheds light on a setting that enables the development of a large number of research collaborations that originate and develop in relation to a single organisation.

We delve in the depth of collaborations originating within a specific organisational settings by studying how scientific collaborations between instrument scientists and users unfold at a successful, user-oriented LSRI, *Institut Laue Langevin* (ILL), known as one of the world's leading research facilities for neutron science (Rush, 2015; Hallonsten, 2016a). Our research draws on a qualitative study of collaborations involving 12 scientific instruments at ILL. Based on interviews with instrument scientists, we identify four typical patterns of collaboration between instrument scientist and users, the conditions enabling their formation as well as their outcomes. These collaboration patterns have implications for the development of collaboration networks of instrument scientists over time and complement one another in addressing two fundamental challenges that user-oriented LSRIs have to tackle: growing the organisation's user base and, at the same time, accommodating expert users to ensure instrument development at the leading edge of science.

Our findings contribute to the literature on research collaboration by shedding light, and extending research, on how collaborations unfold in a highly relevant organisational context for conducting science. In particular, two blind spots in the literature are addressed (Bozeman et al., 2013) – the study of interaction in context and an emphasis on the processes of collaborating. On the level of individual instrument scientists, our findings help better understand the nature of collaboration and suggest more deliberate management of individual collaboration portfolios over time. On the organisational level, our findings suggest that LSRIs should strive to create conditions fostering the development of all four collaboration types and seek to exploit their complementarity for broadening and strengthening their position in their respective scientific fields.

**2. Theoretical background**

The present paper focuses on LSRIs as a specific organisational context for collaborative scientific work. Over the past decades, science has become more and more collective (Bozeman and Youtie, 2017; Cummings and Kiesler, 2011) with an increase in both the frequency and the importance of scientific collaboration (Bukvova, 2010; Sonnenwald, 2007). This process mirrors increasing specialisation, together with the growing importance of complex instruments, escalating cost, and changing funding patterns of scientific research (Katz and Martin, 1997), creating a situation in which single-investigator research has completely disappeared in some scientific fields (Bozeman and Boardman, 2014; Sonnenwald, 2007). In the following sections, we first highlight the growing importance of shared research infrastructures (Section 2.1), then address previous work on organisation types and contexts of research collaborations (Section 2.2), and finally discuss the extent to which LSRIs have been examined as organisational settings within which scientific collaborations unfold (Section 2.3).

**2.1 The growing importance of shared research infrastructures**

Scholars' attention to shared LSRIs over the last decade has led to various attempts to define what a research infrastructure consists of and explore the rationale underpinning their establishment. Building on Qiao et al. (2016), who proposed an analytical framework for the evaluation of the functions and effects of large research infrastructures, we understand LSRIs as large-scale research facilities that require large investments and complex engineering and networking efforts; these infrastructures are usually primarily funded by national governments, shared by communities of scientists, and most often involve scientists permanently based at these facilities as well as external scientist-users.

Scientific collaborations have always spanned organisational borders; many research questions are simply too broad to be tackled by a single laboratory and require cross-discipline and cross-border cooperation. In general, these collaborations used to be driven by initiatives within scientific communities and their international networks. However, as public science budgets began to impose stricter limitations on the growth and expansion of big science (Weinberg, 1967), complex research infrastructures were too expensive to be run by one organisation or country alone, the incentives for sharing costs across nations increased, and international cooperation at all levels of research became a necessity (Elzinga, 2012). There is increasing evidence on the extent to which collaborations unfolded around shared research infrastructures because they enabled more efficient research processes (Vasconcelos et al., 2012). For instance, more than 50 synchrotron radiation sources in operation in the world have served areas of science ranging across chemistry, biology, physics, material science, medicine, and industrial applications (Bilderback et al., 2005). Other examples of shared research infrastructures include, for example, neutron sources, such as ILL in Grenoble (France) and the ISIS Neutron and Muon source in the UK, or laser facilities, such as the Central Laser Facility coordinated by the UK's Science and Technology Facilities Council (ESFRI, 2016b).

LSRIs have become a topic of interest and priority among funders, political bodies, and decision-makers (Lossau, 2012), although the goals of these infrastructures remain heterogeneous. Three types of shared research infrastructures can be distinguished: on one end of the spectrum, we can find large organisations with a focus on specific topics in fundamental research (Galison and Hevly, 1992), such as CERN, hosting the world's largest particle accelerator and allowing scientists from its 22 member states to join on the basis of five-year limited contracts (Autio et al., 2004); centres of this kind typically assemble large teams of collaborators within the same project. On the other end of the spectrum lie widely shared and sometimes de-materialised infrastructures that can be used by a large number of external researchers for a wide range of scientific purposes. Examples of this kind such as information-technology enabled scientific community infrastructures, have been characterised as "collaboratories", which enable synchronous communications and remote-access technology (Bos et al., 2008). In between these two extremes, there are so-called "experimental platforms" (Qiao et al., 2016), which are characterised by an organisational model in which highly-qualified "instrument scientists" interact with "users", that is external scientists who typically apply for experimental time to conduct research at a specific instrument, normally for a limited amount of time. The timeline of experiments can range from few hours on a synchrotron radiation facility to several weeks for a complex experiment at a neutron source. Regularly, collaborations between instrument scientists and users do not limit themselves to "one-off" interactions, instead they give rise to pluriannual research projects spanning multiple experiments and thus yielding a longer-term flow of research activities and scholarly publications involving instrument scientists and external users. In terms of collaboration dynamics, experimental platforms constitute a particularly interesting settings since most of them – contrary to large, dedicated infrastructures addressing a narrow range of research topics – do not define their own research projects, and therefore need to aim for both developing longer-term collaborations with users and fitting a wide range of (potential) users' scientific interests. The particular form of repeated collaboration in the context of LSRIs has not been sufficiently addressed by traditional research collaboration literature.

**2.2 Research collaboration: organisation types and contexts**

The primary objective of scientific research is the pursuit and creation of knowledge, and over the past decades there has been a shift away from research produced by individual scientists toward team-based production (Wuchty et al., 2007). Scholars have widely emphasised how this trend towards collaborating is visible across methods and measures employed to assess collaboration, nor is it specific to certain disciplines (Leahey, 2016). Over the past decades, collaborations among scientists have been in the rise, and this is the case "for every country and every scientific field measured” (Shrum et al., 2007:18) so that, in terms of the shift towards collaborative research, similarities across fields outweigh differences (2007:197).

 Since the late 1990s, the study of research collaboration has developed into a major research area, drawing on various disciplines including social study of science, sociology of knowledge, policy, organisation, and innovation studies. Research collaboration studies have examined issues such as the growing importance of collaboration in science (Adams et al., 2005; Bozeman et al., 2013; Jung et al., 2017), individual collaboration strategies (Bozeman and Corley, 2004; Katz and Martin, 1997; Melin, 2000; Hackett, 2005), collaboration outcomes (Rigby and Edler, 2005; Goddard and Isabelle, 2006), and the organisation of collaborative projects that involve large research teams (Chompalov et al., 2002; Shrum et al., 2001). Methods used have included ethnographic inquiry (Knorr-Cetina, 1999), comparative case study research (Chompalov et al., 2002), large-scale surveys (Stokes and Hartley, 1989; Ponomariov and Boardman, 2008; Bozeman and Gaughan, 2011), social network analysis (Fleming et al., 2007; Ghosh et al., 2015; Wang and Hicks, 2015), and bibliometric analyses (Glänzel, 2002; Hou et al., 2008), addressing multiple levels of analysis and their interaction (Bozeman et al., 2013). An exhaustive review of the research collaboration literature lies beyond the scope of the present study, and we refer readers to the recent reviews published by Bozeman and Boardman (2014), and by Bozeman and Youtie (2017). Unsurprisingly so, the proliferation of the above literature has spawned many definitions of research collaboration; despite so, they all seem to suggest that, at the core of any kind of research collaboration, lie "social processes whereby human beings pool their experience, knowledge and social skills with the objective of producing new knowledge" (Bozeman and Boardman, 2014:2), regardless of how the collaboration is operationalised (Boardman and Corley, 2008).

 Whereas early work on the organisation of collaborative science has been marked particularly by the study of collaborations within large teams of high-energy particle physicists (e.g., Knorr-Cetina, 1999; Chompalov et al., 2002), subsequent work has set out to explore different aspects of research collaborations, such as the aim of a collaboration in relation to new knowledge creation (Leahey and Reikowsky, 2008; Foster et al., 2015; Leahey, 2016), scientists' attitude towards collaboration (Hara et al., 2003; Bozeman and Corley, 2004; Leahey and Reikowsky, 2008), or the type of audiences the collaboration brings together (Georghiou, 1998; Jappe, 2007; Luo et al, 2009; Hsiehchen et al., 2015).

Focusing on the organisation of collaboration, Chompalov et al. (2002) identify four different scenarios of collaboration involving large teams of collaborating scientists (Chompalov and Shrum, 1999; Chompalov et al., 2002; Shrum et al., 2007), emphasising two dimensions – the degree to which collaborations rely on hierarchical organisation and the degree to which they formalise division of labour and entail knowledge differentiation between partners. These dimensions resonate with the dimensions highlighted by Melin (2000) in the study of research collaboration between individual scientists, that is: the specific logic of coordination and decision making present in an interpersonal collaboration and the degree of division of labour among the partners involved. According to Melin (2000), collaborative relationships among individual scientists can vary along a continuum ranging from clear division of labour (e.g., projects are coordinated in all aspects by one partner) on one end to the predominance of mutual discussion and intellectual exchange taking place even before the start of a project on the other end.

The contributions by Chompalov et al. (2002) and Melin (2000), while examining the degree of formalisation and division of labour characterising multiple collaboration types, focus on the interorganisational and individual levels of research collaborations, respectively. Nevertheless, the rising importance of specific organisational forms such as collaboration-driven, user-oriented LSRIs illustrated earlier brings to light the importance of exploring research collaborations by focusing on the interdependence between the organisational and individual levels. This research aims to do so by considering individual scientists' approach to the collaboration and the mechanisms through which the organisational context enables these collaborations to unfold. We thus respond to earlier calls for research on the exploration of research collaboration on multiple levels (Corley et al., 2006; Youtie et al., 2006). Boardman and Corley's (2008) work on collaborations in the context of university research centres constitutes one of the few, if not the only contribution that has made a stride in this direction. By examining the multidisciplinarity, size, and tie centrality of collaborations between university research centres and private firms, they highlight which attributes map to the expected collaborative behaviours. However, by conceptualising collaboration types primarily in terms of institutional origin of collaboration partners, their study does not explicitly address the interdependence between the individual and organisational levels.

**2.3 Research collaboration at LSRIs**

Collaborations among scientists at LSRIs differ from those among scientists based in universities or more traditional research laboratories, particularly because collaborations in the context of LSRIs are often shaped by inter-institutional agreements and thus indirectly driven by policy objectives (Lauto and Valentin, 2013) designed to fund user-oriented experimental platforms such as LSRIs. Previous research on LSRIs has typically focused on exploring, through bibliometric methods, the scientific productivity and impact of these organisations for performance evaluation purposes, through a focus on the relevance of co-authored publications and citation indexes (e.g., Galison and Hevly, 1992). However, a quantitative approach to evaluate research in these settings emerges as rather controversial, even in comparison to traditional scientific laboratories (Hallonsten, 2014). Heidler and Hallonsten (2015), for example, argued that these infrastructures serve first and foremost as user facilities, hence their core purpose of providing excellent technical research opportunities.

The dependence of LSRIs on users for the quality of scientific production – it has been argued that some of these infrastructures need users more strongly than their users actually need the facility (Hallonsten, 2016b) – makes them an interesting setting from an organisational point of view. A unique characteristic of these facilities lies in their capacity to provide services for a broad range of users and it is this access to specialised infrastructure provided by LSRIs to a diversity of users that fosters collaborative relationships with them (Lozano et al., 2014). Yet, this diversity of potential collaboration partners brings with it some costs: as the distance among disciplinary areas grows, the costs attached to the learning process of individuals, teams, and laboratories increase (Llerena and Meyer-Krahmer, 2003).

The above literature emphasises how LSRIs host unique types of scientific collaborations and, as such, constitute a relevant research setting to study. The review also conjectures that often these empirical settings are primarily assessed through quantitative approaches, such as bibliometric data on co-authorship and citations; whilst these bring insight on major contributors to the advancement of various scientific disciplines, they may oversee the factors encouraging or hindering the formation of *new* collaborations. In other words, these measures focus on the outcomes (publications), but tell us very little about the ways in which the research process leading up to a publication was carried out (Bozeman et al., 2013). In addition, extant literature on LSRIs points out the difficulty of steering and controlling scientific development through research policy and organisation, for instance because leading scientists tend to define policies within government bureaucracies (Hart and Victor, 1993) or the financial governance of the large-scale facility tends to favour certain projects as opposed to others (Lozano et al., 2014; Schuetzenmeister, 2010).

 Previous research on collaboration in LSRIs is scarce. To the best of our knowledge, Lauto and Valentin’s (2013) recent work on international collaboration at a U.S. based neutron facility is the only published study analysing patterns of scientific collaboration among scientists at user-oriented LSRIs. In their study, the authors conceptualised shared research infrastructures to reduce scientific coordination costs (i.e., use of shared technologies and instrumentation) and subsequently to enhance the standardisation of research practices. Moreover, through the “agglomeration of specialised scientific and technical capabilities” (2013:387), LSRIs increase the visibility of permanently affiliated researchers in scientific communities. In terms of the general drivers of scientific collaboration identified in the literature, Lauto and Valentin (2013) argued that lower coordination costs lead to a situation in which collaboration is less affected by the factor of geographic proximity and distance of collaboration partners. Although providing valuable insight into the specific aspects of international scientific collaboration at LSRIs, their contribution does not focus on the overall conditions and strategies of resident scientists driving the persistence of collaborative ties. Yet, exploration of these mechanisms is relevant for science policy as well as to better understand how LSRIs are set up and managed.

Building on the previous work on LSRIs, this paper seeks to advance our understanding of collaborations in LSRIs by focusing particularly on the interdependence between the individual and organisational levels of collaboration within this specific organisational setting.

**3 Methods**

In order to address our research aim, we set up a long-term research project to explore drivers and processes of scientific collaboration in LSRIs by combining individual, instrument, and organisational level data from a large and successful international research facility in the field of neutron science (see our presentation of the research context below). Researching a single facility using neutrons across all of its instruments ensured stable structural and organisational conditions across research instruments and enabled the comparison of collaborations across scientists. In what follows, we present our research context (Section 3.1) and what underpinned the data collection and analysis (Section 3.2).

**3.1 Research context**

The research underlying this paper was carried out at *Institut Laue Langevin* (ILL), a leading research centre in neutron science (Rush, 2015), located in Grenoble (France). ILL was founded in 1967 by the governments of France and Germany; the United Kingdom joined as third associate country in 1973. In addition to the three founding countries, ILL is governed by 10 member countries including Austria, Belgium, Denmark, Italy, Poland, Slovakia, Spain, Sweden, Switzerland, and the Czech Republic. It provides expertise and facilities – over 40 scientific instruments for neutron diffraction and neutron scattering – to more than 1,500 scientific users from more over 40 countries to conduct about 800 experiments per year. ILL has an annual budget of about €100 million, and represents an overall investment estimated at €2 billion (ESFRI, 2016a:60). About 70 percent of its budget comes from France, Germany, and the UK, and 20 percent from its other member countries (http://www.ill.eu).

 Beyond its recognition as the "best reactor source optimised for neutron scattering applications" worldwide (Arai and Crawford, 2009:14) and its role as the foundation of the EU's "leadership position in neutron research" (Rush, 2015:17), the organisational model of the ILL also served as a blueprint for the design of LSRIs in other scientific domains, such as the European Synchrotron Radiation Facility (Hallonsten, 2009:224). Taken together, its five decades of operation as a leading facility in neutron science (ESFRI, 2016a) and its "exemplary experience" in the constant improvement of instruments and neutron flux (Arai and Crawford, 2009:27) make the ILL a unique success case for studying LSRI-based scientific collaborations, potentially yielding relevant policy implications.

 As of October 2018, ILL employs 501 permanent staff including 73 instrument scientists (i.e., chemists, physicists, biologists, crystallographers, as well as specialists in magnetism and nuclear physics) who are responsible for operating and developing their respective instruments (in their role of “instrument responsible”), for facilitating the experiments of users (in their role as “local contact”), and for pursuing scientific research agendas of their own. ILL instrument scientists initially join the organisation on a 5-year fixed-term contract. After three to four years, they can apply for a permanent contract, which is granted based on scientific performance and available positions. Normally, each instrument is staffed with two scientists and one technician. In addition, ILL includes support functions such as the reactor group, which operates the nuclear reactor generating the neutron beam, various forms of technical support (e.g., cryogenics), security staff, a library facility, and the user office which manages the project proposal submission and selection process of the scientific projects as well as the overall development of ILL’s user community.

 User scientists from ILL's member countries apply for "beam time" on specific instruments via a formalised process of proposal submissions whereby their research experiments are examined by independent scientific committees based on scientific merit; successful projects are allocated beam time and their proponents can conduct their experiments at ILL. The selection process is competitive; the demand of experimental beam time is usually more than twice as high as the available time on an instrument. The so-called “overload factor” expressing the ratio between demand and available experiment days on an instrument varies across instruments, with the most demanded instruments sometimes attaining overload factors of 3.5 or above.

Once a proposal has been selected by the relevant scientific committee, the proposed experiment is scheduled by the scientist responsible for the instrument in accordance with the availability of the users. On the fixed dates, users travel to Grenoble, normally bringing the samples for their experiments (e.g., a crystal) with them. After meeting the ILL scientist assigned as “local contact” (which is not necessarily the person in charge of the instrument), the user and the ILL scientists together with the instrument technician set up the required sample environment (e.g., a specific temperature, pressure, or magnetic field) and conduct the required measurements. Whereas most scientists working in research laboratories are familiar with characterisation techniques involving for example X-Rays, the data generated by neutron diffraction and scattering are often unfamiliar and more difficult to interpret for users. Thus, instrument scientists and users often need to collaborate for analysing and interpreting the data generated by an experiment, and users are expected to either acknowledge the contribution of ILL scientists or – in case of a more substantial contribution – propose co-authorship.

 The length of experiments, and thus direct interaction between users and ILL scientists, varies depending on the types of instrument and experiment conducted. It can range from a single day for some "high throughput" instruments involving mainly standard procedures to one week or longer for more complex experiments. Concretely, this means that the number of different user groups with which ILL scientists interact during a year can range from less than 20 for more advanced instruments to 80 or more for the most "standard" instruments, with an average number of 40 to 50 experiments per instrument.

**3.2 Data collection and analysis**

We collaborated with the ILL user office to select 12 instruments that were representative of the different types of experiments and scientific disciplines present within ILL. Our aim was to collect a rich dataset including both primary and secondary data. The former would regard interviews with ILL scientists and technicians, whereas the latter entailed collecting detailed data on all projects submitted and selected, the users visiting each instrument over the past decade, and publication records for all participating ILL scientists over the period 2000-2014.

Three main phases of data collection can be identified: in Phase I (Spring 2013), we conducted a pilot study with different informants such as instrument scientists, the head of the user office, and one member of the support staff (4 interviews in total). Drawing on an initial interview guideline based on prior research on scientific collaboration, we were aiming at better understanding how ILL functions and what dynamics underpin collaborations at the site. We then proceeded with Phase II, the main phase of data collection (Winter 2013 - Spring 2014), during which we conducted interviews with 24 permanent ILL staff (23 instrument scientists and 1 technician) collectively per instrument. The interview guideline included questions about the interviewees’ professional and scientific trajectory before and since joining ILL, the characteristics of the instrument and the experiments which they conduct, and their concrete practices of interacting with users before, during, and after an experiment. During this phase, we also assisted in a workshop involving ILL users, discussed our emergent understandings during five meetings with the head of the user office (a former instrument scientist herself), and consulted with two external experts in material science to ensure the accurateness of our understanding of the technical issues.

The final, follow-up phase (Phase III, Spring 2016) drew on the preliminary analysis of the primary and secondary data collected in the first round and was centred on scientific collaborations. In this stage, we conducted six in-depth interviews with instrument scientists who had participated in the first round and were selected because of their tenure (more than 12 years spent at ILL) with the aim of capturing the development of collaborations over time. In this second phase of data collection, we delved into the depth of how collaborations with specific research groups originated, how they developed over time, and what led to their termination. Moreover, we sought to understand how the ILL scientists' research interests related to those of their users, and in which ways, if at all, the collaboration pattern of individual scientists reflected changes in their professional trajectory. To elicit scientists' responses and facilitate recall of past collaborations, we prompted scientists with ego-maps of their collaboration networks, and with lists of their most frequent co-authors, which we created on the basis of the secondary data collected in the first phase. Interview length varied from twenty to 90 minutes with an average length of about 40 minutes. They were all tape recorded and fully transcribed – please see Appendix Table A1 for additional interview details.

To follow, we adopted a systematic inductive approach (Gioia et al., 2012) to analyse all interview data and understand the nature of collaborations and their development over time. We carefully coded our interview transcripts to define a first, inductively generated code list; subsequently, by relying on those codes that appeared most theoretically meaningful and empirically grounded, we developed a coding structure more theoretically-oriented in order to distinguish collaboration types.

The coding process lead us to focus on two main analytic dimensions (more details will follow in the findings section below) – perceived neutron expertise gap and perceived co-development focus –, which were consistently present in our interviewees' accounts and enabled us to capture commonalities and differences in their collaboration experiences. In the final round of coding, we used these dimensions to recode all our interview transcripts. We coded all text passages that related to an interviewee's perceived lack of users' expertise and experience with neutrons as "high perceived neutron expertise gap" (e.g., *"New users don’t really know what to write on the proposal… these people who never touch neutrons... it’s a lot of work to bring a new person into the science.*" Instr4[[1]](#footnote-1)). Text passages that indicated instrument scientists' perception that users were highly skilled and experienced regarding the use of neutrons and the ILL instruments, were coded as "low perceived neutron expertise gap" (e.g., *"Experienced users always have additional samples, always have thought ahead, next time they write the proposal they know it’s working."* Instr9). Regarding the second dimension, we coded all passages in our interview transcripts that referred to an absence of interest in longer-term collaboration on the side of users as "low perceived co-development focus" (e.g., "*Finally, you don’t have a real collaboration with these people, because they are independent… the help that they need from you is very limited*.*"* Instr1), and all passages referring to users seeking to engage in longer-term collaborations as "high-perceived co-development focus" (e.g., *"I would say it’s the users who will come back and say, 'Oh, I think here is a very nice subject but I would need your help.'"* Instr1).

In addition to coding our data for the two analytical dimensions, we also retained additional themes that had emerged throughout the coding process, and which further informed our interpretation of the two main dimensions and the resulting collaboration types. These included, for example, activities of ILL scientists in the context of a project; the origin of a tie (e.g., a former colleague, contact through another researcher or user); the nature of the relationship with the user and the type of interaction (e.g., technical advice, creative input, friendship), also taking into account of the specificity of the science or the instrument; the development of the collaboration over time; and the ILL scientist's career strategy.

We corroborated our understanding based on the interviews with a range of publicly available documents on ILL (i.e., annual reports, newsletters), as well as an internal bibliometric study on the publications associated with the instruments and the connected science fields. Finally, we also presented and discussed our findings in the context of an internal research seminar at ILL, which was attended by about 20 instrument scientists.

**4. Findings**

Interactions between instrument scientists and users occurred in a large variety of forms, ranging from one-off interactions in the context of a short, single experiment, in which instrument scientists provided users with relatively standardised service, to intense collaborative efforts whereby instrument scientists and users co-developed and jointly implemented ambitious multi-year research programmes. Insights from our own data analysis led to the development of a matrix of four basic collaboration types among ILL scientists. These types differed according to the extent to which the collaboration partners - instrument scientist and users - were perceived by the ILL scientist to be similar or dissimilar in terms of their (i) knowledge and experience regarding the use of neutrons ("perceived expertise gap"), and (ii) interest in the future development and deepening of the collaboration ("perceived co-development focus"). In this section, we introduce these the two dimensions (Section 4.1); we then focus on the four collaboration types (Sections 4.2 to 4.5); finally, we address the development of these collaborations over time (Section 4.6).

**4.1 Dimensions underlying collaboration types at ILL**

The variety of collaborations at ILL can be ordered along two independent dimensions – perceived expertise gap and perceived co-development focus. With regard to the former, *perceived expertise gap*,we found that all our interviewees distinguished between non-expert users, which they believed to have very little knowledge and experience, if at all, in the domain of neutron science and the use of neutrons in the characterisation of materials, and expert users, whom they perceived as highly knowledgeable and experienced in the use of the ILL instruments. Non-expert users included users who were new to neutrons, coming for example from new ILL member countries *("there is a very high proportion of people coming from new member countries... they are new users... they need my help... they know nothing"*, Instr1), or users who rarely relied on neutrons to analyse their samples *("They just wanted to measure an important property of the sample"*, Instr10). On the contrary, users with low perceived expertise gap were consistently described by our interviewees as *"advanced users"* (Instr11) with a long-standing track-record of visits to ILL (*"regular users, which are using ILL for 30 years"*, Instr7), and often being *"able to drive the experiment ... on their own"* (Instr1).

 For our interviewees, the perceived expertise gap between instrument scientists and users made an important difference in terms of the depth and the development of collaborations over time. Yet, we also found a considerable variety of collaboration practices *within* both high and low-expertise gap user groups, which brought us to explore a second dimension underlying the interaction between instrument scientists and users. This second dimension, which we labelled *perceived co-development focus,* captured to what extent instrument scientists perceived users to be interested in developing a collaboration over time. Users' co-development focus was typically perceived by instrument scientists to be low when users visiting the ILL were not involved in or did not show particular interest in the experiment itself (*"she just came because he was contracted by the principal investigator... and so she... did the experiment and then disappeared, and I have never heard anything from her since"*, Instr6). Another situation of low perceived co-development focus typically occurred when experienced users did not seek advice or involvement with instrument scientists, and in some instances even discarded their suggestions (*"they think that they know everything... whatever you say... sometimes they don’t care, some of them are really like 'I know what I’m doing, you serve me'… they don’t care…*", Instr4). On the contrary, users'co-development focus was perceived to be high when users actively engaged in discussion (*"they invited me to ... give a talk, explaining what neutron scattering is... and how to obtain the data, describing the instruments and discussing"*, Instr1), involved instrument scientists in the development of research ideas and project proposals (*"I gave a presentation at the conference and they said, 'so could you do this?'... that's how it works... then you a write a proposal together"*, Instr6), and started to develop their research agenda around a specific instrument (*"they saw the nice service we gave, the possibilities they have, they became interested... and then they started their own project to convince their funding agency"*,Instr12).

 The two dimensions of perceived expertise gap and co-development focus combine into four distinct, typical collaboration patterns characterising interactions between instrument scientists and users. We propose to label these collaboration types "full service", "complementary collaboration", "instrument service", and "peer collaboration" (see Figure 1 below). Table 1 below summarises the main formation conditions, characteristics, and outcomes of the four collaboration patterns, and Table 2 illustrates the four patterns with a set of representative quotes from our interviews.In the subsections to follow we draw on our empirical evidence to explore all four collaboration types in more detail.

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Insert Figure 1 about here

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Insert Table 1 about here

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**4.2 Collaboration type 1: Full service**

"Full service" denotes a situation with high perceived expertise-gap and low perceived co-development focus. Typical formation conditions included the presence of new and inexperienced users on instruments using relatively standardised experimental procedures. In the collaboration process, instrument scientists played a critical role both for conducting the experiments and for data analysis. Collaborations typically led to co-authorship, and they were either short-lived or involving the development of a longer-term collaborative relationship between instrument scientists and users.

In "full-service" collaborations, users fully relied on instrument scientists for the set-up of the experiment, its running, and the analysis of the data produced during the experiment. For users lacking neutron expertise, "entry level" instruments and experiments facilitate interaction because the underpinning body of knowledge is standardised. Most new users without neutron experience thus begin with adopting relatively simple techniques such as powder diffraction, before some of them may move, over time, to more advanced instruments. For such inexperienced users, instrument scientists played an important role in facilitating and accompanying users' learning about the use of neutrons in relation to their projects, as illustrated by the following interview quote:

*"Most of the ILL users start with powder diffraction and then they go to more specialised things. This is the case for example with [Name] here. We started with diffraction and now he is coming back to ILL to do elastic experiments, which are more complex" (Instr1).*

In addition, many non-expert users, especially those coming from scientific disciplines who did not traditionally rely on neutrons for the characterisation of samples (e.g., biologists), required assistance also in the project design and proposal submission stages.

 "Full service" collaborations also comprised users who would conduct experiments at ILL repeatedly and over an extended period of time, without engaging in a close relationship with that instrument scientist, that is, without establishing what our interviewees characterised as a "real" collaboration:

*"Another third of users... is not really a collaboration... we just have a local contact without really being involved in that project, we are not involved in the data analysis"* (Instr11).

Lack of users' commitment to learning about neutrons and pushing their analysis beyond what is possible with a given experiment was identified by our interviewees as a reason why interactions may remain in a "full service" mode without developing into a longer-standing collaborations. Several of our interviewees referred to users lacking interest in engaging with neutron science at a deeper level (*"Sometimes people are just not interested. They know what they want, so they just tackle it, everything works, and they just disappear again'*, Instr11).

 Another set of reasons underlying the persistence over time of "full service" collaboration patterns related to the relative standardisation of some instruments and experiment types. The utilisation of certain techniques (e.g., powder diffraction, or small-angle neutron scattering) is standardised in such a way that users are not required to develop their own technical expertise regarding a specific instrument. The limited user involvement (and limited user investment required) in "full service" interactions was a factor contributing to the limited duration of collaborative engagement. As one respondent emphasised, *"it is easy to learn, and it easy to forget also"* (Instr1).

 To renew their user base, instrument scientists sought to convince new, non-expert users to employ neutrons for analysing their samples. Conference presentations and invited talks played an important role in attracting new users to ILL, but also constituted an opportunity for individual instrument scientists to start new collaborations, as illustrated by the following interview quote:

*"They are biologists and they are terrified. I'll meet them at conferences... and we'll start the discussion. And they often have a problem, they've to do something, they want it solved. And I can say, 'Oh, why don't we do this?'"* (Instr6).

**4.3 Collaboration type 2: Complementary collaboration**

"Complementary collaboration" is characterised by high perceived expertise gap between instrument scientists and users in combination with high perceived co-development focus. Formation conditions at ILL included users who were experienced enough to project longer-term involvement with neutron science, yet still required the complementary expertise of instrument scientists to co-develop and carry out experiments. Complementary collaboration typically led to a flow of collective projects over an extended period of time that sometimes broadened through the involving third-party collaborators and persisted over time through the involvement of doctoral students.

 This collaboration type typically developed when interactions with non-expert users were carried out over extended time periods. This collaboration type built a strong sense of complementarity of knowledge and expertise between instrument scientists and users and typically involved the development of a shared theoretical interest. We found that shared theoretical interest acted as a strong driver of enduring interaction in this type, especially when instrument scientists could bring a well-defined theoretical expertise to the users' projects, in addition to their instrumentation and measurement knowledge. The following quote is illustrative of this form of interdependence between parties:

*"So if you come here to look at a magnetic structure... some people are already specialist, but many are not. They have a vague idea. They come here and do the experiment, but they depend heavily on the local contact, people like [Name] who are really routinised in exploring the data. [Name] has got a very large expertise in this field of magnetism and... he has knowledge that the others really need"* (Instr1).

Complementarity between users and instrument scientists played a major role, enabling mutual learning throughout interaction in collaborative projects, as reflected in the following interview statement:

*"The point is the complementarity because they know a lot on the sample... and then they come to do a spectroscopic experiment and... they find someone who is more involved in spectroscopy and can do things in the right way"* (Instr10).

Establishing enduring "complementary collaborations" required intense personal exchanges, for instance across series of project proposals or mutual visits, which allowed to shape a joint research agenda and develop a sense of mutual interdependence. A closer look at our empirical evidence brings to the fore the extent to which instrument scientists tried to establish this trustworthy, long-term collaboration with the users in many ways. The following quote for instance is illustrative of the persuading attitude of the instrument scientist towards the user and the professional (and personal) reward deriving from co-authoring a proposal to submit to ILL:

*"There is another case with a German group, there was someone I had to convince for three hours... after a conference near Tokyo, walking through a garden... to perform measurements at ILL. Half a year after that meeting... we wrote a proposal and that was successful and, since then, we continue to collaborate. I will visit him soon because I want to know more about his techniques of hardening materials, because that's what the collaboration is about"* (Instr2).

Users' difficulty to apprehend a specific analytical approach or instrument was a factor that enhanced the duration of collaboration over time. In other words, "complementary collaborations" relied on both the acquisition by users of a high degree of knowledge in the instruments, methods, and data analysis techniques required for an instrument, and *at the same time* a sense of persistent expertise gap with the instrument scientist – as one interviewee put it, developing such users *"is a warranty that they will come back to us"* (Instr1). In addition, we should also note that underlying "complementary collaboration" was the need for both sides to mutually acquire or exchange expertise. The following quote is illustrative at this regard:

*"When you have these users, then they come back again and again and again, so... you have to... build the network, train them, and then train them well, so that next time it would be easier for you and vice versa. At the end, they would be expert users"* (Instr4).

**4.4 Collaboration type 3: Instrument service**

"Instrument service" distinguishes collaborations that are characterised by low perceived expertise gap and low perceived co-development focus. In our case, such collaborations formed when highly experienced neutron users came to ILL to conduct their autonomously designed experiments. In this situation, the instrument scientists' role was typically limited to providing stable working conditions. While this type of collaboration did not normally lead to co-authorship with instrument scientists, it played an important role in the development of ILL instruments over time.

 Expert users collaborating in "instrument service" mode did not require support and collaboration with ILL scientists beyond basic assistance in their experiments including, for example, ensuring specific working conditions or sample environments on an instrument. Several of our interviewees emphasised how these constellations were problematic for them as instrument scientists because of the difficulty to establish a scientific exchange and longer-term collaboration with such expert users, as in the following illustrative quote:

*"Users that are very independent… finally, you don't have a real collaboration with these people, because they're independent. They need very limited help from you and sometimes… your users tend to consider you as a technician. They go home with their data and finally, two years after, they publish"* (Instr1).

In "instrument service", users often relied on specific ILL instruments for very long time periods, yet they did not engage in establishing scientific collaborations with local instrument scientists because *"they know exactly what they want"* (Instr11), or, as other interviewees pointed out, *"they don't need us for writing the proposal […] or data treatment, because they can do it themselves*" (Instr7), *"they want the instrument and they need assistance on the instrument, but they don't need a scientific input."* (Instr11). The autonomy and primary focus on instrument service of these users was negatively resented by some of our interviewees, as in the following statement:

*"I am not a service man ... I am a scientist who is on the same level as [the users] ... I am not a better engineer or a technician, I am a physicist. ... As a physicist you can give service, but you must be looked at by your collaborators as being on the same level, an equal level"* (Instr12).

Sometimes, strong user expertise could give rise to tensions in the interaction, hence a feeling of frustration among instrument scientists, for example, when experienced users chose to discard the recommendations made by instrument scientists:

*"People coming here on a regular basis tend to think that they know everything... sometimes they don't seem to care no matter what you say. Some of them are really like 'I know what I am doing, you serve me...' I got a few of them... You tell them 'That's not going to work', they wouldn't care. Then we say: 'That's your time, if you decide to waste it like that, here is the machine, you know how to run it? Yes? Good for you, good luck!'*" (Instr4).

Despite a sense of lack of recognition and possible tensions related to "instrument service" collaborations, interviewees also emphasised the important role played by highly demanding expert users, who were typically knowledgeable about other neutron sources as well, for ILL's efforts to constantly improve the quality and availability of its instruments. Expert users could, for example, raise challenges regarding both the technical characteristics of an instrument and the knowledge of instrument scientists, as suggested by the following quote:

*"We had a very famous user from Glasgow who said 'I'll never come again to [the instrument] until you have mastered this technique'... now we can do it, I guess, but we really need to practise it"* (Instr3).

**4.5 Collaboration type 4: Peer collaboration**

The final collaboration type, "peer collaboration", is characterised by low perceived expertise gap between instrument scientists and users in conjunction with high perceived co-development focus. In "peer collaboration", users and instrument scientists participated in the same scientific community engaging in the long-term co-development of experiments and instruments, leading to stable and long-lasting collaborative ties.

We observed this form of interaction most clearly in our exchanges with ILL scientists conducting research in the area of particle physics, studying neutrons themselves, rather than "using" neutrons to characterise other materials. Collaborations in this scenario unfolded in a very distinct way; interviewees emphasised that both local scientists and users belonged to the same, highly interactive scientific community – functioning as sites of *"lively interchange"* resulting in *"a high impact small community"* (Instr12) – which had since its beginning relied on the ILL for their experiments. As emphasised by one interviewee, *"this source was, from 1980 to 2008, the only source of ultra-cold neutrons in the world. Everybody in the world who had an interest in this kind of research had to come to the ILL. That means… we know everybody in this field"* (Instr12).

The development of interactions qualifying as "peer collaboration" could also occur when ILL scientists and users developed a strong sense of belonging to a similar scientific discipline. According to one interviewee, the presence of complementary research interests with users could trigger repeated collaborations over time, which would grow not only in terms of number of projects executed together, but also in terms of *"experiment complexity"* (Instr7).Moreover, interviewees recurrently referred to a sense of shared passion as a characteristic of this interaction pattern, as the following quote illustrates:

*"He came all the way from California every time he could, even when he broke his leg, he came with crutches. He loved doing the experiments. ... [Referring to another user] She really grows the sample, she knows the program, she is just so good to work with because she's technically good, she cares about it. They are the people whom to work with, they are passionate"* (Instr3).

In addition to passion, interactions qualifying as "peer collaborations" were marked by the development over time of a sense of shared understanding and mutual trust, as highlighted by another instrument scientist:

*"We have done many experiments together, and the mutual trust ... I mean it can get quite strong. I have sometimes the feeling that users are not just coming back because of the technique, but because ... they can see something and they trust the technique and like to do these experiments. ... There is a lot of social part in there as well, it's not just... logical arguments"* (Instr8).

An additional, important aspects of "peer collaboration" highlighted by our interviewees concerned the role of expert users for the learning opportunities these collaborations provided for instrument scientists (*"When the people are very bright, it's a pleasure because I learn things in return"*, Instr5).

Over time, "peer collaborations" throve on the sense of mutual challenges and excitement, which fostered a shared understanding of progress in a common knowledge domain allowing users to *"participate in the scientific life"* (Instr12) of an instrument group at ILL. One scientist admitted:

*"My favourite group... they always come up with interesting projects, exciting but they are really challenging and it's exciting to do these very challenging things in science because you need to experiment if they are actually going to work!"* (Instr3).

On the other hand, even longer-standing "peer collaborations" would not endure in the absence of a shared scientific interest. Many interviewees referred to their *"own science"* as essential to maintaining collaborations in the long run and emphasised that, sooner or later, a collaboration originating from a temporary interest in a given area would often end after a few experiments (*"For the moment it is a good collaboration, it may produce one or two papers, but then it will die. It is not my subject",* Instr1).

**4.6 Dynamics of development and co-existence of the four collaboration patterns**

The matrix summarising the four collaboration types in Figure 1 above brings to the fore how each interaction could vary temporally as a result of the influence of different factors related to the instrument, the discipline, or the role (as perceived by ILL scientists) that users played throughout the collaboration. For instance, interviewees emphasised how users engaged in a closer relationship, eventually leading to a longer-term collaboration, as they learned more about an instrument or engaged with new theoretical questions after adopting the same method for several years. It is noteworthy pointing out that, whilst the patterns associated with a *high* perceived expertise gap allowed a learning process in which interactions could unfold over time from "full service" to "complementary collaboration" (as users gained knowledge about the use of neutrons and the types of experiments that could be conducted with an ILL instrument), the two patterns involving *low* perceived expertise gap ("instrument service" and "peer collaboration") appeared in our data as clearly distinct and largely incompatible with each other.

 The juxtaposition of the four collaboration types further points to likely pathways of transitions whereby scientists could aim for transforming their collaborations to renew their user base or balancing "unproductive" one-off types of interaction. We can observe that the usual shift was from "full service" to "complementary collaboration" (from upper left to upper right) as users learned more about neutrons and engaged with instrument scientists in the development of longer-term research programmes. A second shift that could occur over longer periods of time was from "full service" (possibly via "complementary collaboration") to "instrument service" for users who would become increasingly proficient (long-standing use of the same instrument) and therefore require almost no further interaction with the instrument scientist. This also means that collaborations of the "instrument service" type, whilst legitimising the ILL's service-oriented mission, hardly favoured further development of its user base: in the instrument scientists’ view, expert users needed an instrument scientist mainly for a smooth run of their own experiment.

Two distinct temporal mechanisms played a role for the development of collaboration patterns over time. First, users learned through interaction with instrument scientists who often proactively engaged with an 'informal' training of the users, for instance about the use of neutrons in their projects or the analytical potential of ILL instruments (*"you have to educate your users, you have to tell them what you expect will happen"*, Instr1); instrument scientists sometimes also aimed at building a group of expert users who, for instance, knew how to interpret the data generated by their experiments (*"if you create a group like this [a specialist in neutrons], the collaboration can last"*, Instr1). Through this learning process, regular users' research agendas tended to align over time with the collaboration opportunities provided by instruments and the involved scientists, for instance by co-developing a research plan for the medium term. As one respondent put it, there were users who at "*every round of proposals come and bring new ideas and proposals, which are sometimes a continuation of what they've done already, or it is something new"* (Instr10).

The second temporal mechanism present in interactions with users with a high perceived experience gap concerned a logic of network development, building up throughout users' academic careers, especially through an increasing involvement over time of users' students and other collaborators. Especially PhD students affiliated with user groups played an important role in keeping *"the user base alive"* (Instr7), in other words: in the stabilisation and development of "complementary collaborations", either through continued collaboration (*"We supervised a PhD student... and now I am collaborating with him"*, Instr1), or through leveraging former students' or users' network ties (*"They will start a collaboration with someone else and then bring them in",* Instr6).

 The four interaction patterns illustrated above were not mutually exclusive. Instrument scientists tended to engage with a portfolio of collaboration types, which appeared to suit the needs and attitudes to collaboration of both parties, though to a different extent depending on each collaboration type. In the section that follows, we draw on our findings to discuss more generally how collaborations at LSRIs unfold as a result of scientists' efforts to nurture certain collaborations as opposed to others, and how they can be combined to meet the longer-term research objectives of an LSRI. The evidence suggests that there is not a single recipe as to how collaborations at LSRIs develop; instead, different pathways co-exist whereby scientists manage their interaction with users depending on these latter's research interests and perceived co-development focus.

**5. Discussion**

This study set out to advance our understanding of collaborations in LSRIs by focusing particularly on the interdependence between the individual and organisational levels of collaboration within this specific organisational setting. Scientific collaborations have risen in volume and internationalisation (Lee et al., 2015) as a result of a variety of factors, including the importance of interdisciplinary research (Stephan, 2012), growing specialisation and the consequent gains from division of labour (Katz and Martin, 1997), the diffusion of the Internet, and the need to develop and access large shared equipment and large databases (de Solla Price, 1986). LSRIs increasingly represent important loci where these collaborations emerge and develop over time, yet very little is known about their relevance for scientific collaborations not only from a policy perspective (Lossau, 2012), but also an organisational one. Understanding the drivers underpinning these collaborations along with the factors affecting them has become an important remit of academic scholarship.

In general, extensive use of co-authorship and co-citation analysis has been made to explore collaboration patterns over time; however, we argue that these approaches are not sufficient to appreciate the value generated by LSRIs as locus of international collaborations, highly specialised experimentation, and fulfilment of public policy objectives (i.e., providing individual scientists with access to expensive instrumentation that would be otherwise difficult to access via their home organisation's resources). In this manuscript we have qualitatively examined the variety of collaboration types at an historically successful LSRI, and how the interactions between instrument scientists and users emerge and evolve over time. LSRIs are indeed particular types of research organisations in which the collaboration is triggered and initially shaped by instrument characteristics and the proposal selection mechanism, rather than by classic drivers of tie formation such as shared organisational foci or status homophily (Dahlander and McFarland, 2013). Our empirical evidence brought to the fore four collaboration types, which characterise distinct forms of interaction between instrument scientists and users, as well as distinct collaboration dynamics over time. Moreover, our findings suggest that the effective functioning of an LSRI may be dependent upon the possibility of co-existence of all four collaboration types to ensure the broadening and consolidation of their user community on the one hand, as well as the improvement and further development of instrumentation on the other.

The theoretical underpinning of our research connects with the literature that treats research collaborations as dependent on personal, structural, or institutional factors (Corley et al., 2006; Landry and Amara, 1998; Wen and Kobayashi, 2001) and its empirical focus allows us to contribute to a broader science policy debate around shared service-oriented, research facilities. In what follows, we discuss first how the above empirical evidence advances our understanding of LSRIs as important settings for research collaboration (Section 5.1) and second, how the organisation of research collaborations in this setting is intrinsic to both the individual and organisational levels (Section 5.2).

**5.1 Advancing our understanding of collaboration in LSRIs**

The effective functioning of organisations like LSRIs is illustrative of the importance of developing shared research facilities, which integrate mechanisms for the professional development of individual scientists as well as offer an environment within which instrument scientists and visiting users can interact and engage in productive relationships, aiming for longer-term collaborations (McEvily et al., 2014). Based on our findings we argue that each collaboration type contributes on its own to the development of collaborations over time; this in turn suggests that the possibility of nurturing the co-existence of a variety of forms of collaborative arrangements between instrument scientists and users supports the successful development of LSRIs over time.

In the context of LSRIs, instruments themselves need to advance and progress scientifically; at the same time, by engaging in longer-term research collaborations with users, instrument scientists have the possibility to (a) better understand users' needs and (b) stay abreast of scientific developments that ought to be addressed by the LSRI. For user-oriented facilities to successfully develop and contribute to the advance of science, there needs to be a balanced portfolio of collaboration types available at organisation and instrument levels.

To start with, in "full service" collaborations there are typically users who do not yet have a longstanding knowledge in the specific technology underlying an instrument; as a result, this constellation is critical to provide users initial access to the services provided by an LSRI. For the LSRI, it means having the possibility to renew their user base (i.e., by lowering their entry threshold). In practice, this also requires recruiting instrument scientists – for example with a background in biology in the case of ILL – who can interact with and engage in "full service" collaborations with new user communities; in our case, having instrument scientists with a biology background proved necessary to overcome the 'language' barrier between physicists and biologists. From the perspective of the LSRI, this constellation may be problematic if kept exclusively as such in the long run; in fact, on an organisational level, LSRIs share an interest to reduce coordination cost and to enhance publication output, which may be achieved through the development of longer-standing standing collaborations – in other words, there is a strong interest in transforming non-expert users into regular, more proficient users. The facility-level mechanisms built in to foster a more intense collaboration with users are various: hosting conferences, allowing instrument scientists to visit users during instrument downtimes, possibility for the instrument scientists to co-author research proposals, or communicating the LSRIs research collaboration strategy through user newsletters. All of the above contributes towards a context that welcomes the development of "complementary collaboration" while enabling instrument scientists to nurture their research agenda.

In "complementary collaborations", the notion of complementarity between instrument scientists and users acquires its strongest meaning. In this collaboration type, instrument scientists and users bring together their expertise and skills; the two parties mutually depend on each other for the completion of the experiment and research activities that follow. From the LSRI's perspective, this constellation constitutes a highly-productive scenario, in which instrument scientists are fully engaged and the expertise of users is fully mobilised. This leads to lower coordination costs through growing mutual understanding and sharing of some expertise, and towards an exploitation mode on both sides (Li et al., 2013) whereby instrument scientists are willing to engage in co-development with users and these in turn are willing to engage in longer-term projects. In other words, the role of the facility as a full service provider for non-expert users contributes to the development over time of "complementary collaboration" as arguably the most productive collaboration type. However, should "complementary collaboration" constitute the only available collaboration type in the long run, it would bring some risks with it because it may jeopardise the chances for renewal of the facility's user base.

By moving to the "instrument service" collaborations, we find permanent scientists interacting with expert users who have acquired a high degree of skill and autonomy regarding a single instrument or experiment type (possibly conducting this type of experiments at multiple, competing LSRIs), bringing a state-of-the-art outsider perspective regarding the technical capacity and performance of the instruments. As a result, it is likely that this category of users is less keen on establishing a long-term collaboration with the instrument scientists and, instead, more likely to use the facility for their own scientific purposes, and challenge the scientists on a technical level. From the LSRI's perspective, this collaboration type is the most difficult to handle not only because users could be demanding, but also because instrument scientists, by feeling that they can add very little to the project of their users, may lose the motivation in the collaboration. There is yet a positive aspect attached to this constellation: because these users have somehow higher expectations than the 'average' user, LSRIs are motivated to keep raising their standards to remain competitive and in a leading position across the various neutron disciplines.

Finally, "peer collaboration" nurtures and supports long-term collaboration. More profoundly, "peer collaboration" provides probably the most important advances for the development of the instruments themselves and allows a LSRI to firmly anchor itself into a scientific community. Users are considered as experts who know exactly what to do and what to expect from their work at ILL. The downside of focusing mainly on this collaboration type would be the high entry cost for the users and that the user network is strongly dependent on individual instrument scientists.

Based on the above considerations, we would argue that "complementary collaboration" constitutes the most critical form of collaboration for LSRIs because it implies a balance between mutual commitment and specialisation of the parties; but this must be complemented by "full service" – to broaden and renew an LSRI's user base – and "instrument service" – to expose oneself to technically proficient and demanding users allowing to advance the quality of instruments and service provided. Noteworthy mentioning that also "peer collaboration" plays an important role since it enables the development of instruments, of the basic science and technology on which an LSRI is built (e.g., neutron science in the case of ILL), and also contributes to the overall legitimacy and scientific standing of an LSRI.

It must also be noted that the interplay of the four collaboration types, whilst dependent on the nature of interaction between instrument scientists and users, is also influenced by other factors of other individual or organisational nature. The former would include, for instance, an instrument scientist's career stage, the extent to which users actually engage in learning about an instrument and its scientific underpinnings, or the development of a personal tie between instrument and user scientists. Organisational level factors would include the specific nature of an instrument, which influences the types of users who can access it, as well as the organisation-level conditions and resources fostering specific collaboration types to develop more easily. Therefore, in our understanding, the design of an effective LSRI requires a combination of both entry-level and cutting-edge instruments to sustain the co-existence of the four collaboration types. In the section that follows, we discuss how collaboration at LRSIs are organised on individual and organisational levels.

**5.2 Organisation of research collaboration at LSRIs on individual and organisational levels**

In this paper we have focused on the variety of research collaboration types within LSRIs and explored how these develop over time. For the different collaboration patterns to unfold, scientists need to go through various learning processes and mobilise a diverse skillset. No interaction type is 'better' than the other, that is, there is not one 'best recipe' for collaboration; however, each collaboration type has different implications for the persistence of the collaboration over time and all of them – in isolation or combined – engender an effect on both the career of individual scientists and the long-term effectiveness of an LSRI. Although individual scientists may due to their individual trajectory favour (or even be 'trapped' in) one single collaboration type, LSRIs, we contend, are fruitful contexts for scientific discovery because they user-orientation together with proposal-based user-selection through independent scientific committees based may provide instrument scientists with numerous opportunities to develop new collaborations or deepen existing ones.

Our collaboration typology in Figure 1 incorporated two dimensions of partner (dis)similarity: perceived expertise gap along the vertical axis and perceived co-development focus along the horizontal axis. The upper-left quadrant ("full service") represents a situation of dissimilarity between the parties whereby one party cannot do the science without the other one: instrument and user scientists are mutually interdependent with regard to the provision of a sample (for the former) and the need to operate the instrument and analyse the data (for the latter). On the opposite extreme ("peer collaboration" type), partner similarity leads to a situation of mutual reliance in which users can work independently from the instrument scientist, but they still collaborate since they share ways of thinking, the science, and the resources, it is like a partnership among equals. In other words, although both similarity and dissimilarity can yield highly productive, long-standing collaborations, when the partners develop a shared co-development focus, "peer collaborations" are those leaning most strongly towards long-standing collaborations.

The concept of (dis)similarity is familiar to the literature on collaborations both at individual (e.g., scientific collaboration, collaborative knowledge creation) and organisational level (e.g., strategic alliances, networks). Building on Melin's (2000) suggestion that, in order to better understand research collaboration, the focus must shift from the macro level (organisations) to the micro level (teams or networks) of analysis to explore the dynamic processes at work, research on (dis)similarity at the micro level has explored the extent to which partners share their organisational foci, value homophily (intellectual similarity), status homophily (same ascribed and achieved traits), and characteristics of cumulative advantage (centrality and resource richness) (Dahlander and McFarland, 2013). Other scholars have defined (dis)similarity as the difference between the focal person (ego network) and his/her network of contacts, which seems to provide social support (Konrad et al., 2017). In all of these studies, scholars examine the case of individuals who actively look for similar or dissimilar partners. More recently, Crescenzi et al. (2016) have defined similarity in terms of proximity (between inventors) of different nature, that is, geographic, organisational, cognitive, social, and cultural-ethnic, in other words, the context of collaboration presents some degree of dissimilarity which is not necessarily sought for. Although their study is based on a different setting, their results brings to the fore how the context may play a major role in facilitating or indeed hindering the formation of open and diverse collaborations.

In this research we defined (dis)similarity between partners who collaborate in the context of LSRIs in terms of (i) perceived expertise and (ii) perceived co-development focus; in other words, similarity is defined in terms of both shared intellectual interest and understanding of what matters to conduct science and run a project over time. Our findings illustrated how the combination of these two factors triggered collaborations of different nature and, as a result, different length. If there is not a shared interest in engaging in further collaboration, even similarity in terms of interest in neutron science may not lead to long-term collaborations, and the same holds vice versa: collaboration among dissimilar partners from an intellectual point of view can happen and last in the long run if both parties share the co-development focus. Whilst the first of these two dimensions resembles Chompalov et al.'s (2002) focus on division of labour and the extent to which the development of the collaboration relies on different expertise, the second dimension enables us to capture the interrelation between the two levels of collaboration, that is, at the level of individual scientists and at the level of the research organisation, thus differentiating among different collaboration patterns and their development over time. This aspect brings attention to learning processes involving scientific and technical knowledge as well as the development of mutual understanding and trust. It follows that the collaboration can shift from one type to another one (e.g., from "full service" to "complementary collaboration"), thus by considering the possibility of the same individuals moving their collaboration from one type to another over time. We foresee this to be a solid starting point for future research, which could focus more systematically on the transformation that research collaborations within LSRIs undergo over time (Dahlander and McFarland, 2013).

In addition, our analytical perspective highlighted how the ways in which collaborations unfold depend also on factors that go beyond the remit of individual scientists. The importance of context has been hinted at in previous research collaboration literature (e.g., Bozeman et al., 2013). Our empirical work demonstrates the importance of context in terms of experimental techniques and instrument characteristics. For instance, powder diffraction is a relatively standardised technique, requiring little adaptation to specific projects. The less standardised the technique, that is, the less knowledge is systematised (D'Ippolito et al., 2014), the more likely the development of the collaboration over time depends on the professional or personal characteristics of individual scientists. It is also noteworthy mentioning that there may exist mechanisms within the LSRI enabling these collaborations. Formal mechanisms include the definition of formal roles (e.g., user, instrument scientist, or technician) or the presence of the tenure track for scientists. Informal mechanisms encompass discussions that may take place throughout the experiment or the perceived willingness of user groups to engage with the science behind the instrument in the long run. Such mechanisms would in turn influence scientists' future choice as to whether it is worthy engaging in a closer relationship next time the same user groups visit an LSRI. In other words, despite the presence of dissimilarity between the parties involved, productive long-term collaborations can happen if supportive favourable mechanisms are in place.

It is common wisdom to believe that collaborators who share research interests are more likely to collaborate (Katz and Martin, 1997); our research brings to the fore how dissimilarity, to the extent that it leads to increased specialisation, may also support productive collaborations that often develop in the long run. Our empirical evidence substantiated this aspect not only at the organisational level – co-existence of different types of collaborations across the LSRI, favouring the co-existence of a broad range of instrumentation – but also at the individual level – despite the cost of learning scientists ought to bear, they benefit in terms of "complementary collaboration" with a larger proportion of their user base.

**6. Implications for management and policy, future research, and conclusions**

Science is traditionally considered a distinct domain of work organisation, and yet, it is increasingly organised around large work groups that pursue a common objective, that is, advancing knowledge, and draws upon a variety of organisational settings and governance mechanisms (Walsh and Lee, 2015). This paper explored how shared facilities like LSRIs – an indispensable tool for the advancement of science in many disciplinary areas (ESFRI, 2011) – represent a specific setting within which scientific collaborations unfold over time.

 Our study addressed types of research collaborations in LSRIs and their development over time; in particular, it has been discussed the extent to which different degrees of (dis)similarity among the collaborating parties can lead to different collaboration patterns, yet contribute to the functioning of the facility and the fulfilment of the broader remit of advancement of science. Two main contributions are identified, which yields some important implications for LSRIs both from a management and policy perspective.

 Our findings discussed above are, we contend, very important for the management and conception of LSRIs from a policy standpoint. For LRSIs to be able to offer standard services, "full service" may be the ideal collaboration type to favour: since users do not need to engage in developing expertise in the particular science underlying the instrument, experiments in full service collaborations could be run in a more standardised way. However, drawing on the concept of dissimilarity among collaborating partners, our findings illustrate that a focus on one collaboration type only would undermine the scientific advancement of an LSRIs; as the above empirical evidence illustrated, the other three collaboration types are equally essential (e.g., "peer collaborations" are key to develop a stable user community and thus important for the development of the instruments). It is also the case that, if collaborations would draw on a high degree of dissimilarity between instrument scientists and users (e.g., "complementary collaboration" type), then there may be an issue of coordination at the instrument or discipline level. In other words, the co-existence of different collaboration types within the same organisation, driven both by individual instrument scientists' decisions and by the structures and resources provided on an organisational level, serves as an important ingredient for the long-term success of LSRIs.

Our study has two limitations that we hope will form the basis for future research. First, our research focuses on one LSRI only; despite this pioneering the field from both a scientific point of view - by hosting cutting-edge scientific experiments - and an organisational point of view - its model having been adopted by other LSRIs - more insight could be gained from comparing our evidence with, for instance, other user-oriented facilities in which the role of users may not be as influential on the nature of the collaboration; this could be the case of synchrotron radiation facilities, in which experiments tend to be more standardised. Second, even though our findings suggest instrument- and organisation-level influences on the (co-)existence of collaboration types, future research could build up on our typology to engage in a more fine-grained, multi-level research about how organisation-level policies and instrument-level affordances shape the nature of collaborations and their development over time; comparative work may also look at collaboration types from a partner (dis)similarity perspective in other collaboration contexts such as university-industry collaborations or interdisciplinary research centres.

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**TABLES AND FIGURES**

**TABLE 1**

**Formation conditions, characteristics, and outcomes of collaboration patterns**

|  |  |  |  |
| --- | --- | --- | --- |
| **Collaboration pattern** | **Formation conditions** | **Characteristics of the collaboration** | **Outcomes** |
| **Full service** | New or inexperienced users depending on instrument scientists' experimental and data analysis expertise.Experiments conducted on "entry level" or "high throughput" instruments employing relatively standardised analytical technologies. | Instrument scientists as service providers for the experiment and the data analysis.Collaboration focus on single, often short experiments. | Short-lived collaboration yielding relatively few scholarly publications, often including instrument scientists as co-authors.Fragmented collaboration networks of instrument scientists.Instrument scientists can become "mentors" for users developing future research using neutrons.Increase of the ILL's user base and starting point for the development of "complementary collaboration". |
| **Complementary collaboration** | Previous interaction of users with instrument scientists at ILL (or other neutron sources).Users with moderate experience in using neutrons in their research.User expertise is insufficient to conduct experiments on their own, but strong enough to envision productive use of ILL instruments. | Single experiments are embedded in longer-term collaborative effort of users and instrument scientists.Interactions emphasise co-construction and complementarity of users' and instrument scientists' scientific expertise.Instrument scientists participate in the development of proposals. | Strengthening of scientific collaboration ties among users and instrument scientists.Confirmation of users' orientation towards neutrons, exploration of new research ideas, without need for users to become highly specialised in neutron science.Involvement of doctoral students and third-party collaborators of users enables the development over time of collaboration networks.Over time, some users develop expertise that can shift collaboration towards "instrument service". |
| **Instrument service** | Highly experienced neutron users, often long-standing users of ILL.Users are technically and scientifically autonomous; they require perfect working conditions at a given instrument, but no scientific collaboration with instrument scientists.User focus on technical excellence, availability and reliability of instruments and sample environments. | Interaction between users and instrument scientists focuses on the set-up and stability of the instrument and the required sample environment.Instrument scientists are considered providers of an instrument in perfect working condition.Users tend to make their expectations explicit and share their experiences from other neutron sources. | Experienced expert users set standards for instrument quality and sample environments and thus contribute to the development of instruments over time.Absence of strong scientific collaboration with specific instrument scientists.Satisfied users regularly return to ILL over extended time periods. |
| **Peer collaboration** | Established scientific community centred around specific instruments.Users and instrument scientists partake in the same theoretical domain.Instrument scientists are considered as peers within the user community. | Users and instrument scientists fully collaborate in devising experiments and in the development of specific instruments.Role differentiation in the collaboration is limited. | Stable collaborative ties based on shared projects and instrument development.Users and instrument scientists share a sense of partaking in the same scientific community. |

**TABLE 2**

**Collaboration patterns and representative quotes**

|  |  |
| --- | --- |
| **Collabora­tion pattern** | **Representative quotes** |
| **Full service** | New users start with powder experiments. … I start with them and then afterwards they learn with me how to interpret the data. ... They need my help. I can give them the help. They are new users, they go to my instrument. (Instr1)I know that for a standard SANS experiment, it doesn’t necessarily mean that if people are coming here it’s a real collaboration. ... The beamline scientists setup the beamline, but then they can do the measurements themselves, they can analyse the data themselves. (Instr8)There are experiments that people do where, actually they take some of the samples, stick it on, press go and it's done. In that sense, they are like a service and need a local contact, they don’t require anything more than that person doing that. ... but we know the best ways to collect the data, we know how to process the data which most people don’t. (Instr5)Now I have a group in Toulouse, France, which is interested in something, possibly likely to propose something for the next round. So, they invite me to visit their University and give a talk, explaining neutron scattering technique and how to obtain the data, describing the instruments... (Instr1) |
| **Complemen­tary colla­boration** | Most of the ILL users start with powder diffraction and then they go to more specialised things. This is the case, for example, of [name], with whom we started with diffraction and now he is coming back to ILL to do experiments in elastic experiments, which are more complex. (Instr1)When you create a group like this, the collaboration can last ... maybe he’s happy with the experiments, the first or second year and then they want to run experiments and this is the case of [name]. He did a lot of experiments in three or four years and then they did almost everything that he wanted to do with neutrons. (Instr1)The point is the complementarity, because they know a lot on the sample, they know a lot and they did the electric measurement; and then they come to do a spectroscopic experiment and then they find someone which is more involved on spectroscopy and can do the things in the right way. ... It was a good fit. (Instr10)It was really very good working together. He depended on me, I depended on him. Well, no, he depended on me, but he brought in something to ILL, a whole technology. (Instr1)They come here since 15 years at least... This is ... strong because the same person has stayed in charge of this field for a long time. He started when he was young... He figured out this instrument is the right one and then we set up the experiment. (Instr1)When we arrive to create a specialist group of users outside the ILL, this is kind of a success for us. Because this is the warranty that they will come back again to us meantime and we keep the community alive. (Instr1)The students have now much higher positions, they still remember me somehow. They remember me and the instruments. (Instr7) I find him a really good collaborator because he’s an extremely good structural biologist... And he understands the meaning of collaboration, so he really understands, “this is what I'm going to do” and he explains it really clearly from the start. ...Also he understands, he is a neutron user, but if I tell him his crystal is not big enough or these are the problems, he understands it and he tries to say, “Okay, so what could I do?... It's quite constructive... When the people are very bright ... it's a pleasure because I learn things in return… and he always has some ideas and different things that can be done. And that's why he’s my favourite. (Instr5) |
| **Instrument service** | They’re making experiments but they’re more or less autonomous… they’re advanced users, they know what they want, they need some kind of help during the experiment, and maybe also the data analysis behind, but they’re completely autonomous. (Instr11)It’s the type of experiment where you find a relatively large number of expert users who are able to drive the experiment basically on their own. Well, we help, but we are not always so crucial as in some other experiments. (Instr1)These groups, I mean they don’t need me in fact ..., they want the instruments and they need help, assistance on the instrument, but they don’t need a scientific input. ... So these people did this technique on their own ... they know exactly what they want ..., but then they go away and do other things. So, it’s a bit difficult to... keep a relation, because they are more autonomous and... they’re too expert… you can’t give them more than that, than the data… and then they continue to do what they want. (Instr11)The problem, if you have regular users which are using ILL for 30 years ... they don’t need us actually. They need an entry point for working on the instrument, it’s compulsory to have a local contact, but they don’t need us... because they do it for many years. (Instr7) |
| **Peer collabo­ration** | I do particle physics. I am interested in the properties of the neutrons. This is a very, very small community worldwide. It’s very important experiments, very cheap compared to high energy physics, but a high impact, small community... Everybody knows everybody... When the Japanese are here they also meet the Russians at the same time, and also the people from PSI ... always five different groups here that makes also a lively interchange. As I said, the community is small and more or less everybody knows everybody. (Instr12)For the large majority of cases it’s the group leaders who come themselves and do the experiment... And what’s happening very often is that we have collaborations between physicist groups and chemists... So, in that sense, a large majority of cases will be on collaboration, which makes the job also for us far more interesting because you get involved in the science, you really have to understand the science of the samples that come, to make a clever measurement. (Instr8)I've been working a lot with the Swiss group. In fact, it’s a neutron centre in Switzerland also. They can do similar things, but here they can go a bit further, because of better instrument testing, a more powerful source... For me for example, I have been involved in several of the student projects with that place, so this has been going on for 15 years, at least I guess. It can be very, very long term. (Instr7) |

**FIGURE 1**

**Collaboration patterns and analytic dimensions**



**APPENDIX**

**TABLE A1**

**Interview data collection at ILL (Spring 2013 - Spring 2016)**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Project****Phase** | **Instrument** | **Instrument type** | **Intervieweerole** | **Interview date** | **Length of recording** |
| **Phase I: Pilot study** | Instr1 | Two-axis diffractometer | Main responsible | 06 Mar 2013 | 90' |
| Instr11 | Three-axis spectrometer | Co-responsible | 06 Feb 2013 | 60' |
| n/a | n/a | Head of user office | 13 Jan 2013 | Field notes |
| n/a | n/a | Support staff | 11 Mar 2013 | Field notes |
| **Phase II: Main data collection** | Instr1 | Two-axis diffractometer | Main responsibleCo-responsibleCo-responsibleTechnician | 11 Feb 201415 May 2014 | 32'20' |
| Instr2 | Strain analyser | Main responsibleTechnician | 19 Feb 201415 May 2914 | 87'20' |
| Instr3 | Single crystal diffractometer | Main responsibleCo-responsibleTechnician | 13 Feb 201415 May 2014 | 40'20' |
| Instr4 | Small-angle neutron scattering diffractometer | Main responsibleCo-responsibleTechnician | 13 March 201415 May 2014 | 45'30' |
| Instr5 | Quasi-Laue diffractometer | Main responsibleCo-responsible | 26 Feb 2014 | 48' |
| Instr6 | Neutron reflectometer | Main responsibleCo-responsibleTechnician | 25 Feb 201415 May 2014 | 45'30' |
| Instr7 | Time-of-flight spectrometer | Main responsibleCo-responsible | 28 Feb 2014 | 32' |
| Instr8 | Spin-echo spectrometer | Main responsibleCo-responsible | 13 Feb 2014 | 41' |
| Instr9 | High-resolution backscattering spectrometer | Main responsibleCo-responsible | 17 Feb 2014 | 33' |
| Instr10 | Three-axis spectrometer | Main responsibleCo-responsible | 12 Feb 2014 | 49' |
| Instr11 | Three-axis spectrometer | Main responsibleCo-responsible | 26 Feb 2014 | 30' |
| Instr12 | Ultra-cold neutron facility | Main responsibleCo-responsibleTechnician | 28 Feb 2014 | 23' |
| **Phase III: Follow-up data collection** | Instr1 | Two-axis diffractometer | Main responsibleCo-responsibleCo-responsible | 28 April 201610 May 201626 April 2016 | 45'45'45' |
| Instr7 | Time-of-flight spectrometer | Main responsible | 28 April 2016 | 45' |
| Instr11 | Three-axis spectrometer | Co-responsible | 22 April 2016 | 45' |
| Instr12 | Ultra-cod neutron facility | Main responsible | 22 April 2016 | 45' |

1. In order to guarantee anonymity of respondents, all the quotes will be referenced at the instrument level. [↑](#footnote-ref-1)