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The Dynamics of Collaboration in Heritage Science

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ABSTRACT

Heritage science is an interdisciplinary field and successful heritage science research by necessity involves interdisciplinary collaboration between researchers with different disciplinary backgrounds and professional experience. Successful interdisciplinary research is challenging, and many issues have been identified both within and outside heritage science. However, within heritage science there has never been an attempt to do an in-depth study of how communication in interdisciplinary research works in practice. This paper aims to address this gap by providing an in-depth exploration of a case study. We present the analysis of the transcribed recording of a five-hour workshop and follow-up interviews with the workshop participants that took place within the framework of a collaborative heritage science research project. The analysis looks in detail at the dynamics of communication in the context of this meeting, identifying the main topics of conversation and the nature of the transitions between them. We discuss the way in which researchers use different physical scales when thinking about heritage material degradation. We identify key features of interdisciplinary research such as the sense of community and the use of language. Recommendations and insights for future practice are presented.

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Interdisciplinary research; heritage science; system dynamics

Introduction

> *Perhaps heritage science is too broad for a single person. Indeed, it may only exist in a network where many minds come together, including scientists, conservators, and conservation scientists.* (Brokerhof 2015)

As Brokerhof (2015) points out in her contribution to the 2013 ICCROM Forum on Conservation Science, the interdisciplinary nature of heritage science is key to its success. Heritage science is an important part of the cultural heritage field, providing a robust evidence base that informs our understanding of the past and enables us to better protect and manage it. The application of science in the conservation of cultural heritage is a long-established practice (Feller 2002a, 2002b; Hill Stoner 2015). The term 'heritage science' has been adopted more recently (House of Lords Science and Technology 2006) to incorporate both the use of science in the conservation of artefacts in museum collections (sometimes referred to as 'conservation science' and 'museum science') and the use of science to conserve and understand heritage buildings and heritage landscapes. That heritage science is a thriving field can be seen by the development of programmes like the United Kingdom (UK)-based AHRC/EPSRC Science and Heritage Programme (Arts and Humanities Research Council/Engineering and Physical Sciences Research Council) and international collaborative frameworks such as the European Research Infrastructure for Heritage Science (E-RIHS) or the Integrated Platform for the European Research Infrastructure on Cultural Heritage (IPERION CH) (E-RIHS 2019; IPERION CH 2019). As the field of heritage science continues to grow and develop, it is critical to reflect on the way we work.

Heritage science is an interdisciplinary field (Lorusso, Braida, and Natali 2018). The impossibility of a single professional having all of the necessary skills and expertise was pointed out by Chiari and Leona in 2005 (Chiari and Leona 2005) and has been reiterated since. The need for professionals with different backgrounds emerged as a key theme from the 2013 ICCROM (International Centre for the Study of the Preservation and Restoration of Cultural Property) Forum on Conservation Science (Brokerhof 2015; Golfomitsou 2015; Heritage and Golfomitsou 2015) and has been emphasised more recently by Strlic (Strlič 2018). This is part of a broader acknowledgement of the value of an interdisciplinary approach to complex, real-world problems (Holland 2014; Crowley et al. 2018).

Such collaborative working is not straightforward. Issues such as differing language (Golfomitsou 2015) and differing priorities can all lead to misunderstandings and limit the effectiveness and impact of heritage science research. The importance of collaboration is often discussed and these issues have been raised

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many times. However, investigations into the way in which communication works within heritage science collaborations, which could lead to insights and remedies, have been rare. The exceptions are the papers we discuss below (Bell et al. 2014; Dillon et al. 2014; Katrakazis et al. 2018). An investigation of this topic is of increasing utility as the number and complexity of collaborations within heritage science are increasing (Katrakazis et al. 2018).

One issue is the importance of designing research projects that are relevant to heritage practice. The 'Mind the Gap' study (Bell et al. 2014; Dillon et al. 2014) addressed this through a survey of over 200 people engaged in collaborative research projects in heritage science, including both academics and professionals. The study identified key enablers to collaborative work such as shared goals and clear roles. It also identified barriers and problems, including the lower likelihood of satisfaction when it came to achieving practice-related goals, and the increased challenge of working within projects consisting of partners from many disciplines. More recently, Katrakazis et al. (2018) explored how the impact of heritage science research on professional practice can be enhanced through diverse knowledge exchange approaches, open science, and training for researchers in planning for impact.

A second issue is the nature and dynamics of communication within interdisciplinary collaboration between people with different academic backgrounds, knowledge structures, and ways of working. This is the primary focus of this paper, which consists of an in-depth study of an interdisciplinary workshop which supported the direction planning in the initial phase of a five-year heritage science research project. The participants included scientists working both within and outside heritage science and people working at UK museums. We use this analysis to make recommendations for how heritage science practitioners can enhance how we work together.

The methods used during the workshop are from the field of participatory system dynamics. System dynamics modelling has been applied for 60 years and used in a participatory way for about 30 years. It has great potential for heritage science. It is beyond the scope of this paper to give a detailed description of system dynamics because it is not the focus of the paper. However, further explanation of system dynamics is provided in the Supplementary Information.

We propose that this workshop was truly *interdisciplinary* rather than *multidisciplinary*, since the activities of the day involved gathering ideas from participants with different backgrounds and integrating them through causal relationships. Creating models has been identified as a primary tool for integration in interdisciplinary research (Thompson Klein 2015). *Multidisciplinarity* relates to the bringing together of insights and people from different disciplines, but falls short of their integration, whereas the key aspect of *interdisciplinarity* is that these insights are integrated with one another, rather than placed alongside each other (Rutting et al. 2016). The workshop could also be considered as *transdisciplinary*, as it involved collaboration with stakeholders from outside academia (Rutting et al. 2016; Crowley et al. 2018).

It should be borne in mind that this was a small, single case study and the interactions we discuss will reflect the individual personalities of the participants. However, we do believe that our work provides insight into the way in which communication within heritage science works in practice. Unlike any other study that we are aware of, this paper uses an in-depth analysis of a case study to explore the dynamics of communication in collaborative heritage science and uses this analysis to identify key issues, insights, and recommendations for better practice.

Methods

A brief description of the methods used is provided here with significantly more detail in the Supplementary Information.

Workshop summary

This research was based on the analysis of a workshop that took place as part of a heritage science research project that focussed on the degradation of museum artefacts. The workshop was run in a meeting room at University College London (UCL) in November 2017 and lasted from approximately 09.00–14.00. It was attended by 15 people, including one of the authors (NZ) who has a background in system dynamics acting as facilitator and the other author (KC) as principal investigator (PI) of the project. The other participants were staff at UK museums, academic staff, and PhD students from UCL, all of whom were engaged with research in heritage science. Including the authors there were three museum professionals, six members of academic staff and six PhD students present. Three of the participants were male and 12 were female. Some were very new to the field, while others had significant experience. The participants were chosen due to their involvement in the project, or because they were engaged in research related to it. The workshop focussed on the factors that affect the degradation of objects in museums, including policy, environmental and material parameters.

At the beginning of the workshop, the facilitator (author NZ) gave a short introduction to system dynamics and outlined the structure for the day, with support from the project PI (author KC). The participants were asked to identify variables that they thought were significant to the focus of the workshop

and to plot the way in which these could change over time. The variables were then presented and explained. Variables suggested included, 'value', 'relative humidity', and 'additives in the material'. Following this, the variables were incorporated into a diagram, a process led by the facilitator and involving contributions from all participants. This was a long discussion which involved refining the definitions of significant variables in heritage material degradation and of the relationships between them, moving between discussions of science and museum practice.

Transcript analysis

The discussions during the workshop were recorded and the transcript of the recording was analysed individually and jointly by the authors. Analysis of the transcripts from the workshop enabled us to understand the way in which participants interacted with each other, the topics they chose to focus on, and the way in which the conversation evolved i.e. the dynamics of the communication. Follow-up interviews were held with the workshop participants to fill gaps in our understanding that could not be addressed by the analysis of the workshop transcript. Participants were asked about their professional backgrounds, their experience of the workshop, and their experience of heritage science. They were shown photographs of the workshop and asked to respond to excerpts from the workshop transcript. While transcripts of the interviews were analysed by both authors identifying and coding key themes, this paper draws on the heritage-specific interview analysis of author KC. The full list of questions, including the rationale for each one is included in the Supplementary Information.

This paper makes use of classic methods from qualitative research. The approach used in this paper is based on elements of grounded theory, arising from the work of sociologists Glaser and Strauss (Glaser and Strauss 1973). This is an inductive approach, through which a researcher approaches the data without a pre-determined hypothesis, allowing the data to shape the conclusions drawn (Thornberg and Charmaz 2012). Key to a grounded theory approach is coding, through which qualitative data such as interview transcripts is systematically analysed by identifying themes. This usually starts with an initial coding approach, where the researcher takes an open-minded approach to the data, interrogating it broadly to identify the main ideas within it. These initial codes are later developed into focused codes, which are the most significant or frequent initial codes. The text can then be recoded using the focused codes. The final step is to bring together the codes into categories and to use these to draw wider conclusions from the research (Thornberg and Charmaz 2012). Table 1 shows the final codes used in this work, alongside a sample statement for each. The coding approach is described in more detail in the Supplementary Information.

Table 1. Example statements for each code used to analyse the workshop transcript.

Code	Example
Science	*'So the reaction rate is affected by the number of substituents in the molecule'*
Museum practice	*'you might choose to take the lid off a box or move the object away from more delicate materials nearby'*
Both	*'set RH* [relative humidity] *between 40 and 65% and temperature between 18 and 22℃'*
Molecular scale	*'So that's the degree of polymerisation of the polymer'*
Material scale	*'It's whether you think it's become more porous due to degradation, or whether it was porous from the beginning'*
Object scale	*'Colour change is obvious, it's an easy one to spot'*
Community	*'But we do have specific policies written in them to say you should control within that variable'*
Facilitation	*'Anything else in this area of cracking and brittleness?'*

The following sections combine the analysis of both the workshop and interview transcripts. For some of the topics discussed, it has been possible to take a quantitative approach to the data analysis, e.g. to identify the number of statements a particular type of participant made that related to a particular topic. For other topics, a quantitative approach was not possible or advisable and evidence has been provided in the form of quotes from the workshop or interview transcripts. The use of quotes in this way is in line with recommended practice in reporting qualitative research (Tong, Sainsbury, and Craig 2007; O'Brien et al. 2014).

Results and discussion

Workshop participants

To fully examine the dynamics of the communication, it was necessary to understand the participants themselves. In the interviews, participants were asked '*Which of these terms would you use to describe your academic and professional background?*' (Question 1) and were offered terms such as 'Chemist' or 'Conservation Scientist' and also allowed to suggest their own terms. During a follow-up, we also asked, '*Which discipline do you think most informs the way you think about topics like plastics conservation?*'. Using the responses to these questions, we identified four different types of participant excluding the facilitator. These were categorised as follows:

i 'Museum Professionals': this included two participants who worked at UK museums and who did not identify when interviewed with having a scientific background.
ii 'Scientists': this included five participants who identified when interviewed purely as physical scientists, four of whom had no experience

working in the heritage sector at the time of the workshop. The other participant had worked as a museum volunteer but clearly identified their core physical science background (chemistry) as the most important influence on their thinking.

iii 'Scientific Thinkers in Heritage (STH)': this included four participants whose primary training was in science but who had also gained experience of the heritage sector. Through the interviews it was clear that their scientific backgrounds guided the fundamental way in which they approached problems, while their experience and expertise in heritage informed that thinking.

iv 'Heritage Professionals with Scientific Training (HPS)': this included three participants with significant experience in both museum/conservation practice and in heritage science. Based on follow-up interviews, this group was identified as having a core outlook that came from their conservation training, while also being strongly influenced by their scientific training.

This categorisation reflected the academic degrees held by the participants, with the 'Scientists' and STH groups likely to have degrees in scientific subjects and the 'Museum Professionals' and HPS groups likely to have degrees in conservation.

Text from the workshop was also coded based on the topic of conversation as either:

- 'Science' e.g. discussions of mass transport or chemical reactions
- 'Museum Practice' e.g. discussions of storage policies
- 'Both' which included concepts that bridged both categories and those where the individual used terms both from museum practice and from the physical sciences

More detail on coding is provided in the Methods section and in the Supplementary Information. It was clear from our analysis that different categories of participants made different contributions to the discussion overall (Figure 1).

Unsurprisingly, the largest contribution made by the 'Scientists' was to the 'Science' topic, while the 'Museum Professionals' contributed most to the 'Museum Practice' topic, reflecting their specialised expertise. The HPS and STH groups appeared across all topics, but with a larger contribution from the STH group to 'Science' and from the HPS to 'Museum Practice'. This reflects their more mixed backgrounds. The facilitator also contributed significantly to all topics, highlighting the importance of their role. It should be noted that this categorisation is based on the small number of participants in our workshop. Additional categories of participant would likely be identified if other groups of collaborators in heritage science research projects were studied in a similar way. However, in author KC's professional experience, the categories identified here have a relevance beyond this particular group of people and examples of each could be found within many heritage science collaborations.

Dynamics of discussions

The way in which the conversation moved between topics over time (measured by the number of words spoken) was plotted according to the type of speaker (i.e. 'Scientist', 'Museum Professional', STH, and HPS). The results are shown below in Figure 2 and allow the dynamics of communication (who was speaking, about what, and for how long) to be studied in detail. This Figure is also available as an animated PowerPoint slide as in the Supplementary Information, which allows a viewer to see the conversation evolve over time.

The discussion began by the facilitator asking the participants to identify the variables that they felt were most important to the project. This general discussion moved between discussions of science and museum practice. Next, the group was asked to identify a starting point for the diagram. This was agreed to be the emission of volatile organic compounds (VOCs) which started as a discussion based around museum practice, but which moved to a much more scientifically focussed discussion. This can be seen in Figure 2 as a long section where there are no statements coded as 'Museum Practice' and no contributions from a 'Museum Professional'.

After this, the conversation moved back to a more practice-oriented discussion, a transition that was mediated by one of the STH group (see below for further discussion of this transition). This conversation revolved around museum storage. The facilitator later moved the discussion to the topic of light aging, prompted by one of the HPS group, who mentioned that the subject of light had not arisen yet. After this, the PI introduced the subject of chemical reactions.

This led via a discussion of the brittleness of materials to discussions of more museum-focussed topics such as treatment, handling, and training. Brittleness later acted as a transition topic again, leading to a more scientifically focussed discussion and then to a general discussion in which the facilitator asked the group to identify topics that they felt were missing from the diagram. This led to a range of topics being discussed, including museum policy and resources, air exchange rates, and visitors.

The coding enabled us to also look more closely at the points at which a transition occurred between one

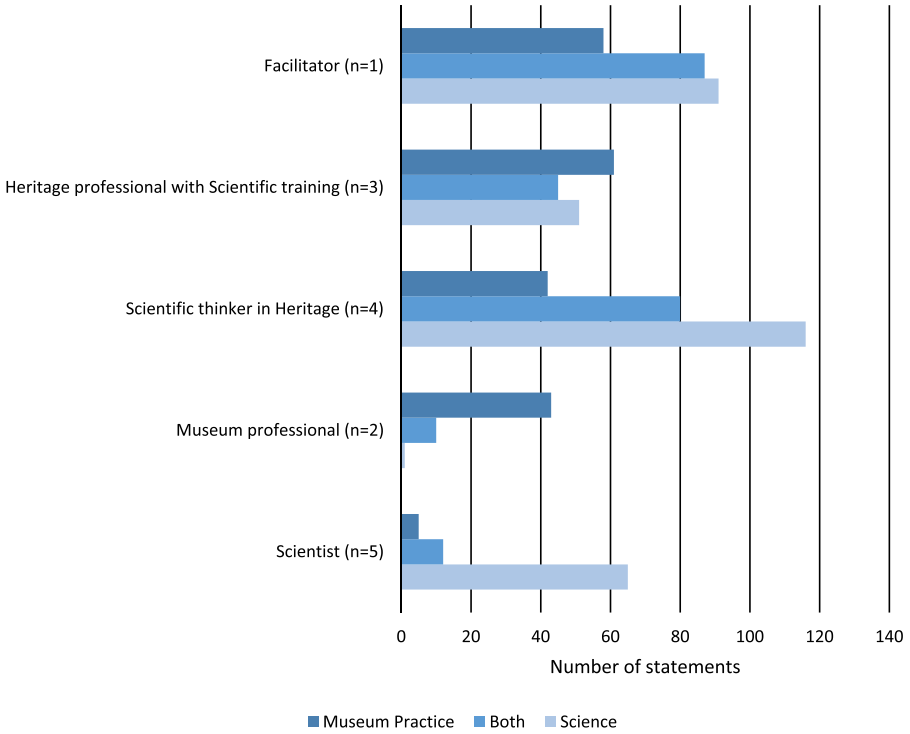

Figure 1. The number of contributions on each topic by each type of speaker.

topic and another, e.g. from 'Science' to 'Both' or to 'Museum Practice'. These transitions took many forms, including facilitation, 'Museum Professionals' turning the conversation to focus more on practical conservation, and 'Scientists' introducing more scientific terminology into the discussion. It also included many examples of remarks or ideas that helped to bridge different concepts. Approximately 20% of the overall statements were identified as transition points (197/1012), showing that a large proportion of the workshop was spent in moving between one topic and another.

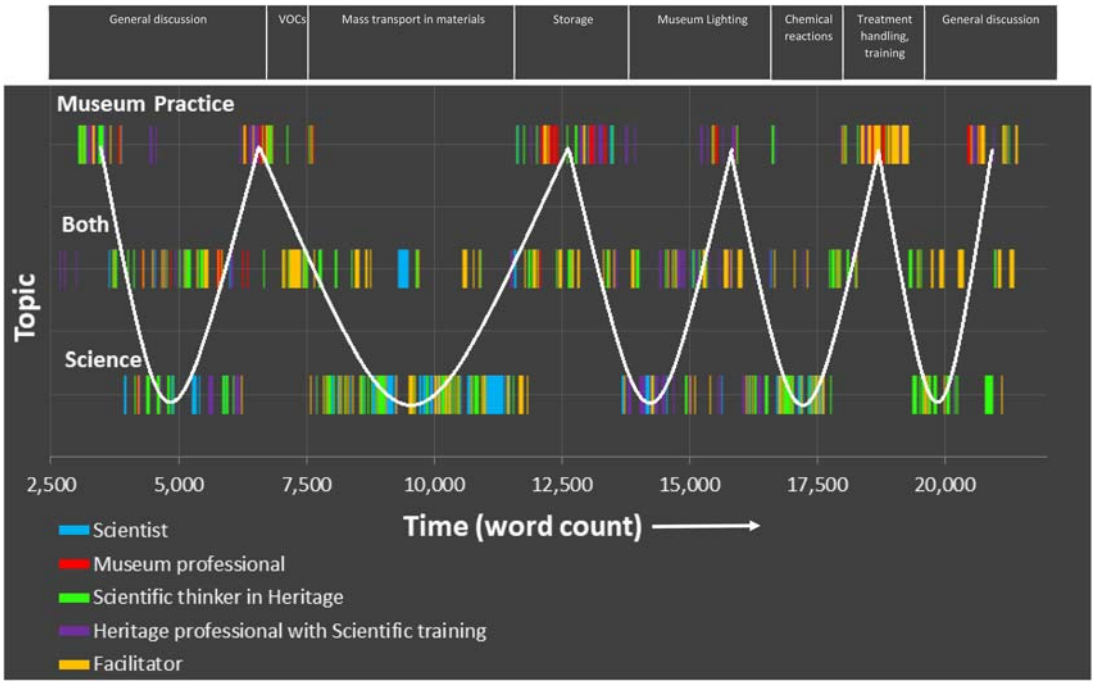

Figure 2. The dynamics of the conversation during the workshop, showing how the topics and speakers changed over time. The colours represent different speaker types, e.g. 'Scientist' or 'Museum Professional'. When these colours appear at the top of the plot, it indicates that the statement made at that time was coded as 'Museum Practice', in the middle as 'Both', and at the bottom as 'Science'. The main topics of conversation at any point are indicated along the top of the diagram. The white curve shows how the conversation oscillated between science-focussed and museum-focussed discussions, although always with some element of both.

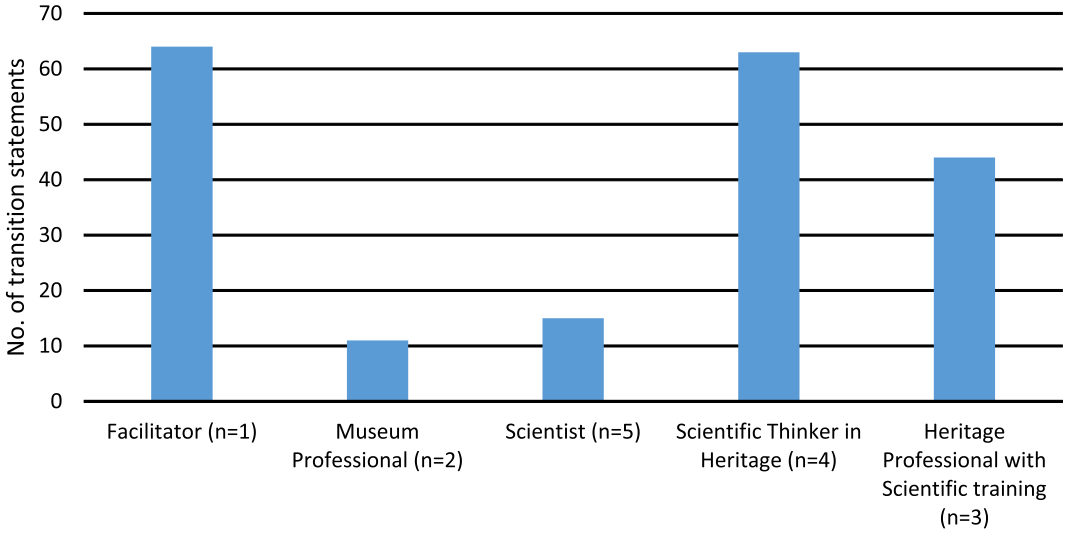

Figure 3. The number of times a member of each different group said something that caused a transition in the topic of conversation.

Different categories of participants had different roles in making transitions within the conversation. The number of 'transition' statements made by each group is shown below in Figure 3. The critical role of the facilitator is very clear; while this is just a single individual, she made the largest number of 'transition' statements compared to any of the groups. The difference between the 'Museum Professionals' and 'Scientists' groups and the STH and HPS groups is also striking, with the latter two groups having contributed significantly more to the transitions. This indicates the important roles of both experience working between fields and of training, in the development of interdisciplinary heritage science researchers.

However, it should be noted that the percentage of 'transition' statements made by each group is very similar to the percentage of overall contributions to the discussion from each group. This means that the facilitator and the STH and HPS groups spoke most often in general during the workshop, which is reflected in their contributions to transitions. There are multiple factors at play here, including individual roles (members of the host organisation or guests, lecturer, or student), the system dynamics workshop design, individual personality traits such as confidence, and maybe even the closeness of participants to the shared whiteboard. It is impossible to disentangle cause and effect and to decide whether the STH and HPS groups contributed most to conversational transitions simply because they spoke most often or whether it is a natural consequence that a conversation dominated by such groups will transition often between different topics.

During the follow-up interviews, participants were shown an example of a transition in the conversation where the topic was moved deliberately by one participant (STH2 in Table 2 below) from a more technical focus on VOCs to a more museum practice-focussed discussion about storage. This was Question 7 in the interview (see Supplementary Information for more detail). Participants were asked what they thought of this approach to guiding the conversation, whether they felt it was effective, whether they remembered trying to perform this role themselves, or remembered others doing so. This transition occurred at approximately word 11,600 in Figure 2 and provided an opportunity for 'Museum Professionals' to speak for the first time in over half an hour. While this very conscious approach was not common throughout the conversation, it is a distinctive strategy for bridging a potential gap between different stakeholders and was felt to merit further investigation.

Many participants felt that such an approach was effective and when asked '*What do you think it takes for someone to be good at this?*' in the interviews, flagged up several factors. These statements do not represent a consensus among participants but rather illustrate a range of ideas identified by them. A summary of these factors is shown in Figure 4.

i *Knowledge and Experience*: 5 out of 11 interviewees raised the value of having experience of both museum and scientific practice and also of interdisciplinary meetings and conversations. This is linked to the importance of groups such as the STH and HPS who have experience in both fields and also suggests that this is a skill that can be learnt with time. It corroborates findings from the 'Mind the Gap' study (Bell et al. 2014; Dillon et al. 2014). One participant mentioned the importance of building from a solid foundation of assimilated knowledge in

Table 2. An excerpt from the transcript of the workshop showing a transition between a more scientifically focussed discussion on VOC migration and a more museum practice focussed discussion about storage.

Speaker	Statement
Facilitator	*Surface to bulk ratio, yes?*
Scientist	*And then there is also what you are doing outside, either removing the VOCs as they migrate, or is it sealed and they stay there? Is it stagnant, the fluid outside, or are you moving it … ?*
STH1	*Ventilation … .*
STH2	*Then it would be quite nice to get into a little bit of detail into this as it relates to storage, so that could be …*
Scientist	*yes because this is what … I guess, do you have to ventilate, or is it better to store it and seal it and keep it stagnant.*

one's own field. This links to one of the ethical principles of collaboration listed by Thompson Klein: Intellectual Confidence, or a sense of accountability for your individual contribution to a research project (Thompson Klein 2015).

ii *Frame of mind*: various related attitudes were highlighted as helping to bridge gaps between museum practice and scientific research. Three participants raised the idea that you need to consider yourself as a bridge or an arbitrator.

I have to think of myself as being in the middle and trying to make the bridge (Participant 4, Scientist)

That we should be conscious arbitrators (Participant 2, Scientist)

consciously making yourself, sort of asking yourself the question about 'okay, so I have this question about this kind of scientific aspect, but how does that relate?' … if you do that regularly enough, it becomes a habit (Participant 3, HPS)

iii *Focus on Aim and Impact:* Other participants emphasised the importance of being focussed on impact and of understanding the aims and motivations of your collaborators. Respect also came up, of remembering that just because someone is lacking in technical vocabulary, it does not mean that they cannot understand a concept.

Another (more junior) participant pointed to the importance of hierarchy and of feeling that you have permission to speak up and intervene in a conversation. Although it did not arise in this study, it is worth considering that other feelings around hierarchy could come into play in such interactions, such as those related to minority identities.

There is much to consider here in relation to communication within heritage science as a field. These findings indicate that two groups of people – (i) individuals with a background in a physical sciences subject who actively seek to gain an understanding of the heritage sector and (ii) heritage professionals who undergo relevant scientific training – have key roles to play as 'conscious arbitrators' who can help bridge good quality science with relevance to heritage practice and thus increase the overall impact of heritage science research.

In addition, having the conversation mediated by someone who did not have expertise in heritage or science helped to make the conversation and the resulting diagram accessible to all participants. It meant that theoretical concepts needed to be communicated with a certain level of abstraction in order to be

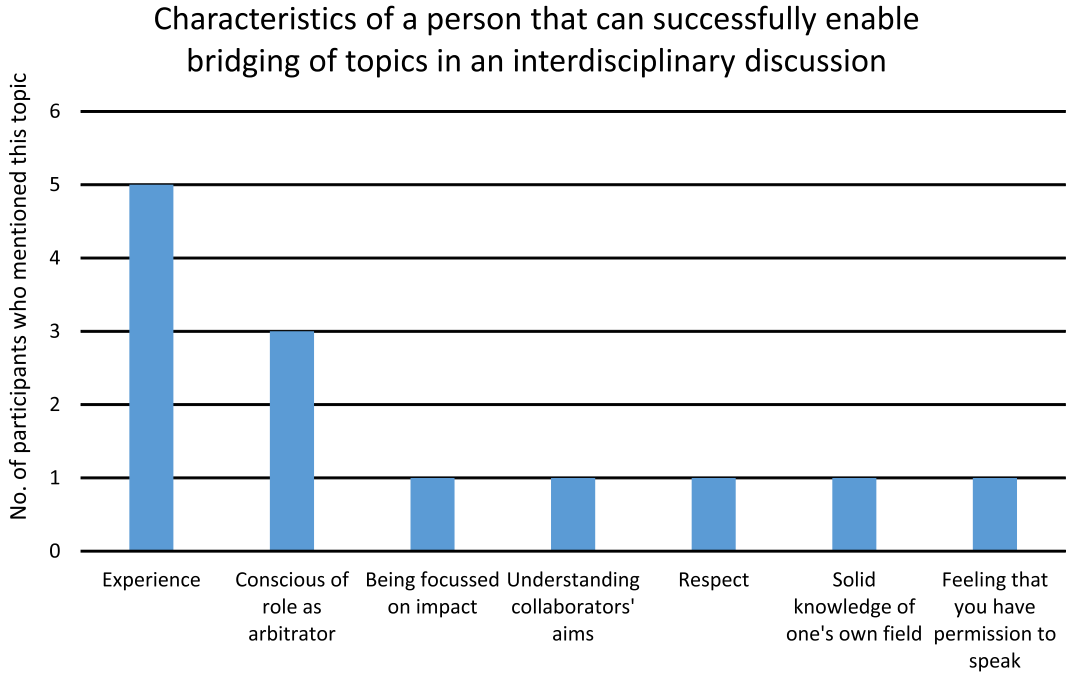

Figure 4. Characteristics identified by the interview participants when asked '*What do you think it takes for someone to be good at this [making successful transitions in interdisciplinary conversations]?*'.

incorporated into the diagram. A further paper on the use of participatory system dynamics as a tool in interdisciplinary research is in preparation (Zimmermann and Curran 2020).

The importance of shared concepts

Our analysis also showed that topics that were coded as 'Both' were very frequent. Excluding any uncoded statements, 30% of the individual statements were coded as 'Both' (27% were coded as 'Museum Practice' and 43% as 'Science').

The main topic of conversation oscillated between topics related to museum practice and those that were more science focussed. This oscillation can be seen by the white curve drawn in Figure 2. However, a closer look at the transcript during each phase suggests that the conversation was more integrated than this might first indicate. Usually, the main topic was made more broadly relevant through the statements coded as 'Both'. During the more scientifically focussed conversations, there were many references to the way in which scientific principles are related to the museum scenario. This was often done by linking underlying physical or chemical processes to more tangible evidence of damage e.g. smell or colour change:

> *… you have a reaction that is caused by the presence of substituents there, water, temperature – this reaction creates an acid – and this acid builds up and eventually it migrates outside and this is what I smell …* . (Participant 9, Scientist)

In a similar way, the more museum practice focussed discussions were often underpinned by a discussion of the relevant physical or chemical mechanisms.

> *We could make the separation between air velocity, like over the surface of the object and air exchange rate in the space where it's stored.* (Participant 7, STH)

The high number of statements coded as 'Both' is important. It shows that there was a conscious effort within this team to make whatever was the focus of the conversation at any given time relevant to the group as a whole. The bridging concept of material change is also important and will be discussed in the next section.

The most integrated part of the discussion was on museum lighting. A reason for this could be that, while photo-degradation is a scientific topic, the issue of light damage to museum collections is very well-known and has been the subject of museum guidance for decades (Thomson 1986; International Commission on Illumination 2004).

It is therefore a topic that both scientists and museum professionals are equally likely to be comfortable discussing, unlike many of the other topics raised on that day, such as chemical degradation, mass transport, museum handling policies, or storage containers, which will be preferred by one group or another. There is a lesson to be learned here about heritage science: as scientific topics become increasingly commonplace in a conservation context and vice versa, it is possible to have a more integrated discussion about them.

Physical scales, mental models, and language

One interesting result that emerged from the analysis of the transcript was evidence that different groups of participants were thinking about heritage materials on different physical scales. The workshop transcript was coded according to whether participants were discussing materials on an object, material, or a molecular scale. The 'Molecular' scale included references to processes or properties on a molecular level such as chemical reactions; the 'Material' scale included processes or properties that are relevant at a sub-millimetre scale such as diffusion; finally the 'Object' scale was defined as relating to processes or characteristics that are visible to the naked eye such as cracking.

These scales may correspond to different mental models or knowledge structures that individuals can impose on information, to give it structure and meaning (Walsh 1995). For example, a chemist will think of materials in terms of chemical bonds, a mental model that operates on the 'Molecular' scale. This will inform their conception of material degradation, whereas the mental model of a chemical engineer, focussed on larger-scale processes such as diffusion (the 'Material' scale), may be quite different.

The transcript was coded according to these scales and the results are shown below in Figure 5a. In order to take into account the different numbers of people in each group, the percentage breakdown for each group of participants is shown in Figure 5b.

Clear differences emerged between different groups. For example, the 'Museum Professionals' mostly used the 'Object' scale, sometimes the 'Material', but never the 'Molecular'. In contrast, the 'Scientists' mostly used the 'Material' and 'Molecular' scales and rarely the 'Object'. The other two groups displayed a more even spread across the three scales, with more emphasis on the 'Object' scale for the HPS group.

These results demonstrated that (within the group at this workshop at least) those without a formal scientific qualification and those with no or very limited experience in heritage (the 'Museum Professionals' and the 'Scientists' respectively) thought about heritage materials in very different ways. While the 'Museum Professionals' took a more practical, object-based approach, the 'Scientists' raised issues about underlying mechanisms such as chemical reactions or diffusion. This difference is worth bearing in mind. A discussion with a collaborator that appears to be about the same topic may be underpinned by very

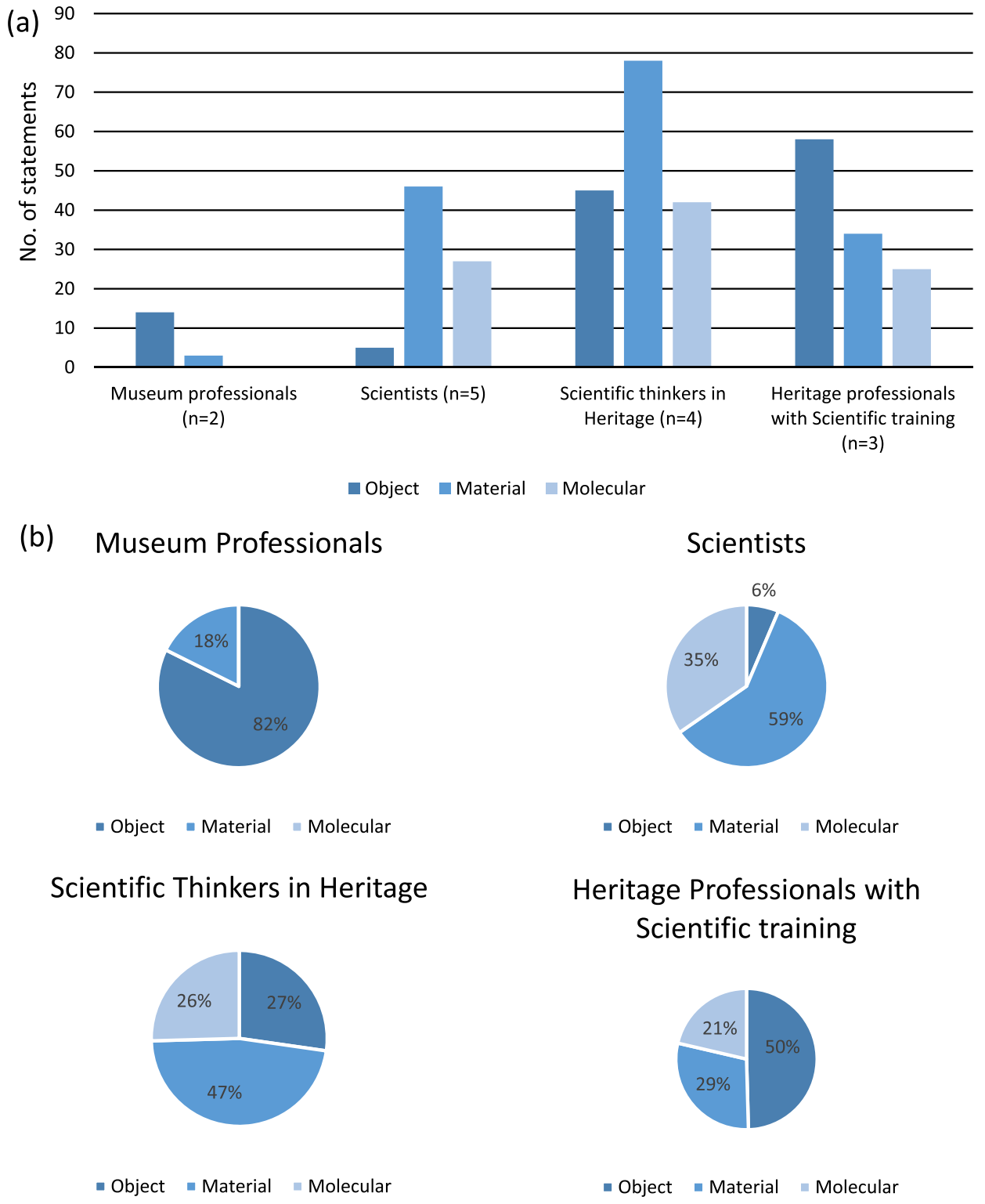

Figure 5. (a) The number of references by different groups of participants to processes in or attributes of heritage artefacts at different physical scales during the workshop and (b) The same data shown as percentages for each group.

different mental models, with one person primarily considering visible effects and the other zooming in to consider molecular changes. This links to the topic of language, as it is worth considering that the terminology one is using may simply have no place in the mental model that a collaborator is applying.

These differences in scale are related to the idea of 'common ground' raised by Holland (Holland 2014). The desire to understand the degradation of heritage materials is shared by all participants, however the concepts and theories used to understand it are different. Discussions of material degradation therefore present an opportunity to integrate different mental models, while respecting the differences between them.

It is worth noting that the STH and HPS groups used terms and raised issues that relate to all three physical scales. The STH group consisted of people who would

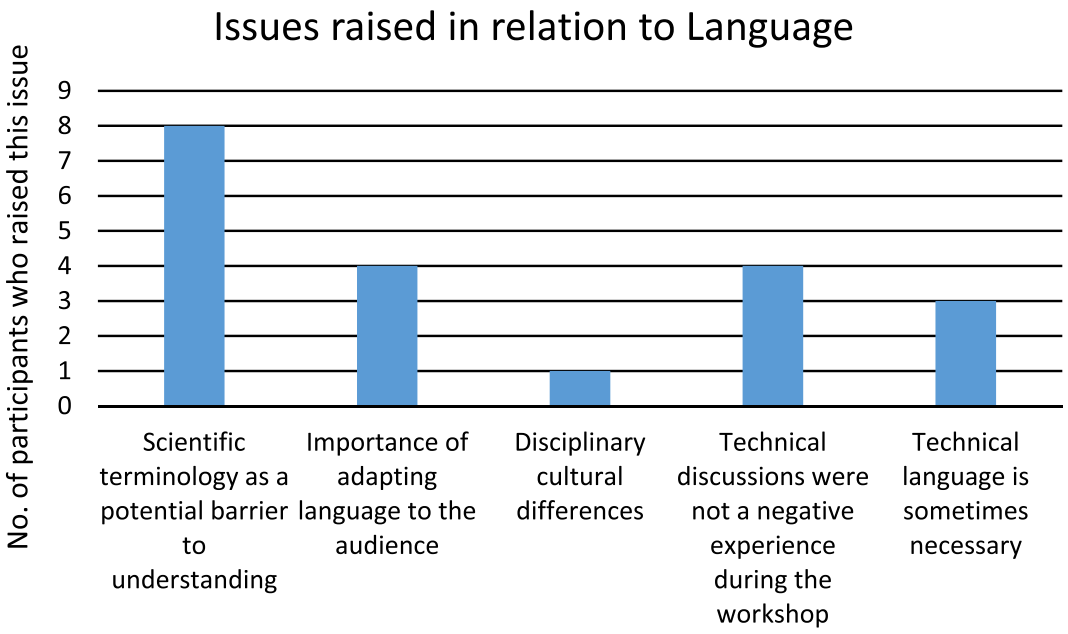

Figure 6. Issues raised by participants that related to the topic of language. Two of these ('Scientific terminology as a potential barrier to understanding' and 'Technical discussions were not a negative experience during the workshop') relate specifically to the workshop while the others are more general issues raised.

have been classified as 'Scientists' at an earlier stage in their careers but who have since had significant experience in the heritage sector. Similarly, the HPS group was made up of those who would have fitted with the 'Museum Professionals' group at an earlier stage in their careers, but who have now received formal scientific training. Our findings suggest that those with a scientific background will begin to take on board ways of thinking that they learn from heritage professionals, as evidenced by their increased emphasis on the 'Object' scale, compared with the 'Scientists'. Similarly, the results suggested that those with a heritage background will gain confidence in discussing scientific concepts after training, as evidenced by an increased use of terms related to the 'Material' and 'Molecular' scales by the HPS group compared with the 'Museum Professionals' group. Overall, these findings point to the benefits of experience and of the value of training and education in harmonising mental models that may have originally been quite different from each other. The importance of training programmes as a key source of scientific knowledge for heritage professionals was previously highlighted in the ICCROM Forum on Conservation Science in 2013 (Golfomitsou 2015).

One further point to raise on this topic is that the opportunity to link the 'Object', 'Material', and 'Molecular' scales is one of the many exciting challenges in the field of heritage science. Within a discipline such as chemistry or physics it is not always relevant to connect (for example) molecular changes to visible colour change; however, moving between these physical scales is very important within heritage science. Giving observable phenomena a foundation based on robust scientific principles is one of the crucial intellectual challenges of heritage science and one that should be embraced and promoted.

As noted, the topic of physical scales also links to language. Language came up repeatedly during the follow-up interviews as a key aspect of interdisciplinary collaboration. Four of the eleven interviewees identified language or terminology when asked to identify the main challenges in collaborative heritage science research. This topic also came up in response to Question 4 in which we asked participants about their experience of the more science-focussed discussions in the workshop and in subsequent questions where we asked '*How easy do you find it to relate fundamental scientific concepts to practical museum conservation issues? What is challenging about this?*' and '*How do you approach this during your daily work? How did you find this in the workshop?*'. Again, we should point out that the ideas presented here do not represent a consensus among participants, rather a representation of the various ideas they raised. These are summarised in Figure 6.

Language and communication come up regularly as a key challenge of interdisciplinary research (Bruce et al. 2004; Dillon et al. 2014; Crowley et al. 2018) but this is perhaps a slightly more nuanced issue than it could first appear. Eight of the interviewees clearly identified the use of technical scientific language as a potential barrier to understanding. Speaking more generally, four pointed to the need to adapt your language to your audience. This reflects the Habermas-Klein thesis that different disciplinary languages need to be integrated (for example by creating a

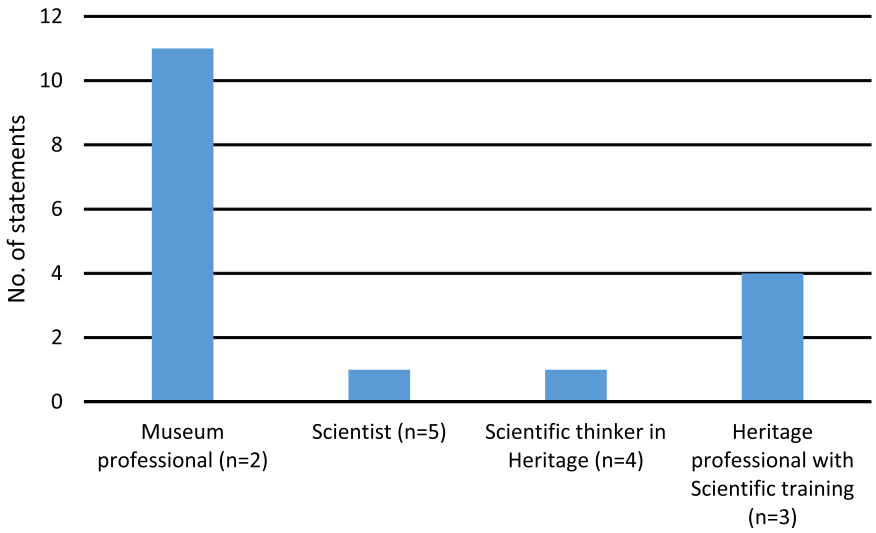

Figure 7. Instances of members of different groups speaking as part of a community.

common vocabulary) to create common understanding (Thompson Klein 2015).

> *but I think just maybe changing the language a little bit, adapting the language to the audience would have helped which I didn't think always happened.* (Participant 3, HPS)

> *If what we say should be understood by everyone, then we should take that sentence and simplify it and explain it in a different way, so that everyone understands.* (Participant 4, Scientist)

While this is undeniably important, it is worth pointing out that four participants expressed a view that sometimes experts needed to communicate in certain ways and that their experience of the workshop had not been negatively affected by this:

> *I didn't find it a negative experience, it was just moments when the experts in that area need to discuss something specifically.* (Participant 1, Museum Professional)

> *I do remember there being quite a technical discussion which was interesting from my point of view because I'm not a chemist – some of these things were new to me – so it was interesting to see the back and forth that they were going on, I enjoyed that.* (Participant 10, STH)

In addition, three participants pointed out that some scientific concepts simply cannot be expressed in everyday language, or at least not without lengthy explanations.

> *very often, there is scientific terminology that summarises three or four things that it would take a couple of sentences to say in the usual, spoken language.* (Participant 7, STH)

> *I don't think he could have said this without saying those things, he would have just not had to talk at all.* (Participant 2, Scientist)

We propose that there is a need to strike a balance between the fact that technical terminology can exclude people and the recognition that not all language can or needs to be adapted. One participant identified this as a key role of the heritage scientist:

> *I think, putting forward optimised ways to speak about things is part of our job as heritage scientists.* (Participant 7, STH)

In terms of how this 'optimisation' can be achieved, some ideas emerged from the interviews. Two participants pointed to the importance of trying to identify what the listener is trying to understand from the discussion. Two participants pointed to the need to respect your audience.

> *not having that formal education which means that some of that language is automatically lost on that person which is not to say that they can't understand it.* (Participant 10, STH)

> *you don't need to know the word 'migrate' and 'stagnant' in order to understand what's going on.* (Participant 7, STH)

There are ideas for improving interdisciplinary communication in the academic literature also. For example, Leigh Thompson highlights the importance of including trust-building and social time in a project, and of explicitly discussing language and communication issues (Leigh Thompson 2009).

These are important ideas for the heritage scientist to reflect on, as their experience in the field develops. We need to consider the language we use in collaborative discussions. Sometimes a discussion will relate to a small, highly specific aspect of a project for which global input would be needlessly time-consuming and technical vocabulary is the most appropriate. In other cases, it will be worth making the time to agree on and normalise a common vocabulary, or risk excluding points of view that would otherwise enrich the research outcomes.

Sense of community

Often people come to an interdisciplinary meeting with a feeling of being part of a specific community e.g. as a chemist or as a conservator. Bronstein's model of interdisciplinary working includes the concept of *Interdependence,* which

> *refers to the occurrence of and reliance on interactions among professionals whereby each is dependent on the other to accomplish his or her goals and tasks. To function interdependently, professionals must have a clear understanding of the distinction between their own and their collaborating professionals' roles and use them appropriately.* (Bronstein 2003, 299)

We recognise that an in-depth understanding of the way in which heritage science researchers identify with different communities is beyond the scope of this paper. However, we do feel that our analysis provides some useful insights into the way in which the participants in our workshop felt themselves to be part of particular academic or professional communities and how that influences their role in the discussion.

Several comments were coded in the workshop transcript as indicators that the speaker was thinking of themselves either as part of a disciplinary community or as a member of an organisation. This was much more common among the 'Museum Professionals' (Figure 7).

Often, the 'Museum Professional' was speaking as a member of their organisation e.g.

> *But we do have specific policies written in them to say you should control within that variable.* (Participant 5, Museum Professional)

> *… but I don't know because within our policy, there's lots of different aspects of light exposure.* (Participant 1, Museum Professional)

This showed that the museum staff present were aware of their roles as representatives of their organisations. The difference between the 'Museum Professionals' and the other groups may also be because of what the groups deal with on a daily basis. Working in a museum is a joint team effort and involves interaction with multiple colleagues, which is a somewhat different dynamic to that of an academic staff member or a PhD student. It may also be a question of seniority, as one of the 'Museum Professionals' also identified as a Manager and may thus be more likely to talk in terms of 'we' than a more junior employee with a narrow responsibility.

There were also clear examples of people considering themselves as representatives of their academic discipline e.g.

> *I'm not a chemist and a chemical engineer is very different from a chemist.* (Participant 9, Scientist)

> *But as a conservator, it would cause us to react. It causes … if it's an enclosed box, we might take the lid off, or call the scientist.* (Participant 5, Museum Professional)

In this context, it is important that each member of an interdisciplinary heritage science project is aware of their role, in the context of their discipline or organisation. Depending on their expertise, each has a specific set of knowledge or ideas to contribute, without which the project overall would be weaker. The findings from this section demonstrate that the group was composed of individuals who came to the workshop with multiple senses of identity, related to their professional and academic backgrounds. The authors suggest that a balance is needed between valuing our own and others' individual roles while also considering how to work together as one group.

Recommendations and insights

The results suggest a number of recommendations and insights for researchers in heritage science to apply to their communication practice.

i Integrated discussions within heritage science research in which all contributors feel valued are achievable. Participants with experience in both heritage and science have key roles to play in facilitating transitions between topics of interest to different groups.
ii There exist specific tools and processes to aid integrated discussions that can be applied in heritage science, such as the use of participatory system dynamics methods.
iii Education within heritage science is operating in two different directions; individuals with a core background in a physical science are gaining experience of the heritage sector and others with formal training or experience in the heritage sector are receiving scientific training. Both these groups were shown in this study to have a key role in bridging the language and mental models of those with more specialised experience.
iv There are two roles for the heritage scientist to consider adopting when engaging with an interdisciplinary group, that of a 'conscious arbitrator' and as an 'optimiser of language'.
v The physical scales of the mental models used by different types of researchers is a key area of difference between those of different backgrounds and a potential area of common ground if these differences can be explored and connections made. Connecting the molecular, the material, and the object is an exciting intellectual challenge within heritage science.
vi It is important to be aware of our individual role in an interdisciplinary discussion. Consolidated

knowledge in our specialism is an important contribution, which potentially nobody else in the team can make. This needs to be done with a sense of intellectual integrity.

Conclusions

Heritage scientists and museum professionals have a responsibility to reflect on the way in which our critically important interdisciplinary communication is working and how it can be improved in the future. This paper explores the dynamics of communication within interdisciplinary collaboration in heritage science by using the case study of a workshop. The authors have tracked the dynamics of the interdisciplinary conversation that took place, exploring how the main focus of the conversation moved between topics related to science, museum practice, and those that included both aspects. We have identified the groups of participants who took part in discussions on each topic, how transitions between topics were facilitated, and key themes that emerged from the analysis including language, physical scales, mental models, and sense of community. We use our analysis to provide key recommendations and insights for improving interdisciplinary collaboration within the field, such as the roles of heritage scientists as conscious arbitrators and optimisers of language. While the small and particular nature of this case study needs to be borne in mind, we believe that this will provide insight for current and future heritage scientists into the nature of and challenges associated with working in an interdisciplinary field, with a view to improving future collaborative practice.

List of abbreviations

HPS: Heritage Professionals with Scientific Training.
STH: Scientific Thinkers in Heritage.

Authors' contributions

Authors KC and NZ jointly developed the concept behind this paper and both collected, analysed, and interpreted the data. Author KC wrote the first draft of the manuscript, which both authors revised and discussed.

Declarations

Availability of data and materials

The datasets generated during the current study (transcripts of interviews and workshop) are not publicly available as they contain information that would allow identification of workshop participants. An animated PowerPoint slide of Figure 2 and a document describing the methodological approach in more detail are available as additional files in Supplementary Information.

Competing interests

The authors declare that they have no competing interests.

Ethics

Formal ethics approval for the research project within which this study took place was obtained from the Director of Ethics at the Bartlett School of Environment, Energy and Resources (BSEER), University College London. Written consent for participation in the study was obtained from all participants before the workshop took place.

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