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Conducting Research in the 21st Century: How Life Scientists Conceptualize, Operationalize, and Value Interdisciplinary Research

by

Alexander C. Gardner
Graduate Student Researcher, Department of Higher, Adult, and Lifelong Education
Michigan State University

and

Benjamin Espinoza
Graduate Student Researcher, Department of Higher, Adult, and Lifelong Education
Michigan State University

and
Chelsea Noble
Graduate Student Researcher, Department of Higher, Adult, and Lifelong Education
Michigan State University

and

Marilyn Amey
Faculty member and Chair Department of Higher, Adult, and Lifelong Education
Michigan State University

and

Dr. Patricia Farrell-Cole
Evaluation and People Development Specialist
Van Andel Institute.

Abstract: This study explores how life science researchers conceptualize, operationalize, and value Interdisciplinary Research (IDR). We interviewed a sample of 10 established life science faculty to understand the researchers' lived experiences and perspectives on participating in IDR. Six themes emerged from our data: (1) IDR requires the integration of insights from different disciplines, (2) IDR can occur within disciplines, (3) Collaborators should be intentionally selected, (4) Differences in languages must be reconciled, (5) Authentic and frequent collaboration is required, and (6) IDR is valued by life scientists because it broadens our understanding of complex scientific questions and produces great scholarly rewards.

Keywords: interdisciplinary collaboration, interdisciplinary faculty, interdisciplinary STEM research, life sciences, science and technology centers

Introduction

Scientists from across disciplines and knowledge domains have been called to work together to solve grand issues facing society (Disis & Slattery, 2010; National Academies of Science, 2005; Wuchty, Jones, & Uzzi, 2007). Funders including the NSF and NIH require interdisciplinary research to solve these complex problems. However, the life sciences scientific community that supports interdisciplinary research (IDR) finds this research slow to gain support from multiple departments and even from their own disciplines (Cumming & Kiesler, 2008). Further, those who do work across academic disciplines face major challenges arising from this form of teamwork (Ledford, 2015). Academic disciplines collide and clash in important ways related to how to approach a problem, what methods to use, and even what conclusions to draw as a result of the elements differentiating disciplines from one another (Repko & Szostak, 2012).

Because of the challenges and complexities of IDR, the National Research Council (NRC) has brought together content experts across scientific and engineering disciplines to identify opportunities to develop effective IDR collaborations between those in science and engineering and other disciplines (NRC, 2015). However, despite such efforts, as of 2019, experts have declared there is still little congruence across theory, areas of inquiry, practice, and methodologies of collaborative research. For these reasons, additional research focusing on the scientific, social, and philosophical aspects of collaborative research is needed to understand and ultimately improve the processes that propel knowledge production in IDR teams (NRC, 2015).

Purpose of Study

The purpose of this study was to investigate the perspectives and experiences of researchers participating in IDR. Our target population was established life

science faculty (e.g. faculty in biology, biotechnology, genomics, proteomics, bioinformatics, and pharmaceuticals) actively involved in IDR, as evidenced by their having obtained grants for and completed the work they'd proposed and published with their collaborators. Our research questions were

1. How do life science researchers conceptualize interdisciplinary research?
2. How do life science researchers operationalize interdisciplinary research?
3. What do life science researchers believe is the value of interdisciplinary research?

Although researchers may desire collaboration, it can be difficult to engage in as social, financial, and organizational barriers can individually and/or collectively inhibit collaboration (Bozeman & Boardman, 2014; Kezar, 2005; Kezar & Lester, 2009). Should those barriers be overcome, the team members still have to reconcile differences in work style and disciplinary norms, as well as agree on a topic, approach, methodology, timeline, and work-sharing arrangement (Baldwin & Austin, 1995; Hara, Solomon, Kim, & Sonnenwald, 2003; Leahey, Beckman, & Stanko, 2017). Researchers may thus start IDR work at a disadvantage compared to those who engage in disciplinary-specific work because those who primarily research within their discipline do not have to navigate all the pluralism collaboration across disciplines brings with it (Miller, Baird, Littlefield, Kofinas, Chapin, & Redman, 2008; O'Rourke & Crowley, 2013). However, as proclaimed by Keestra (2017), collaboration is well worth all the effort involved: "It is important for all scholars – including in that term scientists and other academic experts – to realize that each theoretical account [of a problem provided by a team member from one discipline], focusing on one or more determining factors involved, has usually only a limited relevance" (p. 126) whereas IDR work has an enhanced ability to study and solve problems more holistically.

A shared passion for solving problems is important for collaborators, but evidence suggests with whom one works also matters, sometimes even more than the focus of the work itself. Building respectful and trusting relationships is critical (Melin, 2000) for the development of a strong foundation that will support ongoing work. Being part of such a network can create a shared sense of purpose and promote the sharing of information and resources required if that purpose is to be fulfilled (Wray, 2002). Furthermore, research has supported the importance of having an interdisciplinary facilitator who is able to engage in and across multiple forms of disciplinary discourse, effectively serving as an IDR "translator" for those on the team (Lash-

Marshall, Nomura, Eck, & Hirsch, 2017; Repko & Szostak, 2012). This leader must also be wise enough to avoid taking the path of least resistance by simplifying the problem under study and suppressing differences in points of view. Instead, leaders must push team members to achieve a new level of understanding informed by the multiple disciplines involved. How exactly this work is done and conceptualized by life science IDR scholars is the major area this study seeks to address.

Methodology

The purpose of this exploratory study was to understand how life scientists experience IDR and for that, qualitative rather than quantitative research was necessary since qualitative research is interpretive in nature, grounded in the lived experiences of participants (Glesne, 2015). An interpretive interview approach was utilized in order to uncover individual perceptions critical to understanding what life scientists believe about IDR. According to Patton (2002), interviewing allows researchers to enter the perspective of another individual. Of course, as Patton argues, the quality of information obtained is dependent upon the quality of the methods the interviewer adopts, and for these reasons a number of "high quality" information-gathering practices were adopted. For example, while there are a number of different ways one can interview, we used an interview guide consisting of questions addressing issues to be explored over the course of the interview (Patton, 2002). This more structured approach ensured specific topics were covered with each participant such as how participants conceived of IDR, how they conducted IDR work, and what they believe separated IDR work from non-IDR work (see sample questions in the Appendix). Similar information was gathered from each participant so we could compare responses across individuals and ensure each participant's voice was heard on a given topic. In total, over 720 minutes of audio interviews were recorded with the average interview lasting just over an hour. Follow up and explanatory questions were asked for clarification when needed.

Sample Selection

As noted earlier, the target population for this study was established researchers who have conducted interdisciplinary work throughout their career and had success in obtaining IDR grants for collaborative work and co-authoring publications with co-workers from different disciplines. Our sample comprised researchers from a National Science Foundation

(NSF)-funded interdisciplinary, inter-institutional Science and Technology Center (STC) that includes more than 200 faculty across five universities representing three primary NSF-defined disciplines: life sciences, engineering, and computer science and mathematics. The STC supports innovative, potentially transformative, complex research and education projects that require large-scale, long-term grants, empowering researchers from science, engineering, and computer science and mathematics to undertake significant investigations at the interfaces of disciplines and/or fresh approaches within disciplines ("Science and Technology Centers," n.d).

We used the Center's 200-member internal database that includes annual productivity data of STC members to purposefully select 10 faculty who met specific criteria: life sciences, grants, interdisciplinary work, and co-authored outputs (Miles & Huberman, 1994). We focused our sample on faculty who are life scientists. Life scientists study organisms and want to understand how the organisms work; they learn about and utilize the scientific method to produce knowledge (Alba, 2017; "Science, Engineering, and Technology," n.d.). Life scientists receive different training than engineers or computer scientists and mathematicians. We elected to focus on life scientists to narrow our focus to a group of researchers who share training and, hence, knowledge of relevant literature and methodologies. Interviews lasted 30-60 minutes, were transcribed verbatim, and coded first by each member of the research team independently for inter-rater reliability. Once team members coded a transcription on their own, codes were then compared as a group and the list of codes used was narrowed for further analysis. Follow-up interviews were conducted to clarify emerging themes and further investigate the life scientists' experience with IDR.

Data Analysis and Coding

According to Saldaña (2015), a code in qualitative inquiry is a word or short phrase that "symbolically assigns a summative, salient, essence-capturing, and/or evocative attribute for a portion of language or visual data" (p. 4). This code is then used to attribute interpreted meaning to individual pieces of data for pattern detection, categorization, theory building, and other analytical processes.

As noted, the present study is interested in ontological questions related to the understanding of IDR, the process of conducting IDR, and the differences between IDR and non-IDR work. Since these types of questions are exploratory in nature and rely on personal interpretation of experience, the

coding must reflect this orientation. For this reason, In Vivo or Literal Coding was selected for the first cycle of coding because it could reflect participants' perceptions, attitudes, and beliefs (Gable & Wolf, 2012; Saldaña, 2015). In Vivo coding is based on what the participants say themselves (Saldaña, 2015) and it thus respects the voice of the participants, which was important to ensure the findings would portray an accurate representation of participant views (Glaser & Strauss, 1967). Responses that pertained directly to the research questions were coded more holistically (i.e. not by isolating just a single quote, but instead by including all of the content that pertained to the topic) in order not to lose any participant meaning. For this reason, in some cases, a series of quotes were captured to accurately reflect the response of a participant. Once the initial In Vivo coding was completed, a second read-through using the same coding strategy was conducted to check whether what was identified was accurate in reflecting the participants' voices and significant; we looked for patterns in responses, which helped crystallize and condense meanings. This second review reflects the work of Charmaz (2014) who used a similar coding pattern and approach.

The series of codes that were developed for the individual interviews were then compared, and similar categories of codes were grouped together to form themes. The initial group of themes were reviewed and evaluated based on how they contributed to understanding the phenomenon under study (e.g., how life scientists experience IDR). The themes were then organized into two categories – those that were essential to our research and those that were incidental. The criteria for this distinction were based on the work of van Manen (1990), who describes essential themes as themes required to accurately describe the phenomenon. The In Vivo statements that were generated directly from the participants' own language during the first round of coding served as the basis for identifying these essential themes. The essential themes identified were woven together during later cycles of coding to identify "processes, tensions, explanations, causes, consequences, and/or conclusions" (Rubin & Rubin, 2012, p. 206). These themes are explored below.

Limitations

We acknowledge several limitations with our research. First, our sample was small, the majority identified as White, and all were associated with the same STC, an STC that favors and supports interdisciplinary research teams. Second, all were willing to participate and interested in discussing their perceptions of IDR and experiences working as part of an interdisciplinary

research team. This may have created a sample of individuals most likely to share favorable views about working in such an IDR team. They may well not be representative of all IDR research team members, especially those not associated with such a supportive and encouraging environment. Also, there are a multitude of social, professional, and economic reasons researchers participate in and value IDR, and we acknowledge that not all of them are accounted for here.

Findings

The purpose of this study was to explore how life science researchers conceptualize, operationalize, and value interdisciplinary research. Several themes emerged from our data based on the research questions under study. When RQ1 is considered (How do life science researchers conceptualize IDR?) two themes emerge: (1) IDR requires the integration of insights from different disciplines, and (2) IDR can occur within disciplines. When examining the data in relation to RQ2 (How do life science researchers operationalize IDR?) we identified three themes: (1) Collaborators should be selected intentionally, (2) Differences in languages must be reconciled, and (3) Actual and frequent collaboration is required. Lastly, for RQ3 (How do life science researchers value interdisciplinary research?) one main theme emerged: IDR broadens our understanding of complex scientific questions and produces greater scholarly rewards than discipline specific research alone. Each of the research questions and themes will be addressed before implications are addressed in the discussion below.

IDR Requires the Integration of Insights from Different Disciplines

When life science researchers were asked to describe how they conceptualize IDR, responses varied in the specifics that were highlighted, but each respondent addressed factors relating to how they perceive IDR or how others perceive it. One common theme emphasized the integration of individuals with different educational backgrounds, knowledge domains, approaches, research methods, languages, norms, and perspectives into a coherent, functional team. When responding to how she conceptualizes IDR, Elizabeth[1] commented,

> I think animal behavior is one of those nice disciplines where you're always sort of working at an interface between various other disciplines. [When doing IDR] You are either working at

[1] When referring to specific speakers in the "Findings" sections it is important to note that pseudonyms are used to protect identities.

> the interface between disciplines or drawing on the tools from one discipline to attack problems that have plagued the other discipline for a long time…Disciplinary work tends to be more narrow and focused and I think interests a narrower array of readers.

This perception of an "interface" is especially resonant because it recognizes that those trained in disciplines have a certain way that they think about and conduct research. When those with different ways of thinking and doing meet and interact, working together can be challenging. This belief was a common one, as Edmund agreed, saying that IDR is "a line of investigation or a line of research that requires multiple areas of expertise that are not likely to overlap." He went on to share that,

> The framing of research questions and the methodology used to answer them can be pretty different between different fields. For example, framing your question [so it] will be adequate to address more than one [issue] in more than one field is another thing that requires [additional thinking].

Edmund also commented that he knows he is doing IDR work "when it involves a technique that's outside of the scope of the abilities of our lab or similar labs, especially when it involves a fundamentally different area of expertise." Clearly, the researchers we were working with do see engagement with different techniques and expertise rooted in different disciplines as an indicator that one is involved in IDR.

Unsurprisingly, responses from our researchers also highlighted the notion that IDR requires the integration of distinct ways of knowing and doing that are traditionally rooted in particular knowledge domains or disciplines. They acknowledge that scientists must recognize and resolve fundamental differences rooted in disciplines to pursue new knowledge or a new line of inquiry. Gerald emphasized the need for integration of insights from different disciplines when he said,

> I would say at first blush that interdisciplinary research to me is collaborative efforts that cross-market disciplines or interface between biology and engineering or biology and computer science and in most of my research those are the disciplines that overlap.

This response was not uncommon in that all the researchers participating in our study made reference to IDR bringing together people from multiple disciplines, and described IDR as a collaborative effort to find common ground between disciplines at points where they intersect or overlap. Some of them struggled to articulate their conceptualization, but at the root of their responses, each emphasized the importance of integration of insights that those from different disciplinary backgrounds can provide. Dennis

epitomized this struggle when he commented,

> I hate trying to define it [IDR], because it's not like I consciously choose to do interdisciplinary research, it's just that I think about a lot of things and I can't not think about things...[I] talk to people outside of my discipline…I think that interdisciplinary research is working with people who can answer questions that you could only answer with great difficulty, and probably more important working with people who can ask questions that you wouldn't think of asking. That's not maybe as necessary, but there's people who can ask questions that I wouldn't think of asking and I wouldn't have a dream of how to answer [them], but I wouldn't think of that as interdisciplinary for me as much.

Researchers agreed that collaboration from multiple disciplinary experts was required in order to identify and then achieve the integration of insights necessary for the successful pursuit of interdisciplinary work.

IDR Does Not Exclude Work Within Disciplines

Another aspect of IDR that the responses of our researchers highlighted is the belief that IDR can happen within a discipline as well as between disciplines. For example, Anna said the following when she was asked how she conceptualizes IDR:

> [It often involves] bringing together…very different fields: biology, computer science, and engineering…kinds of collaborations that truly integrate those different fields, [but] that doesn't describe all the projects. In fact, there's quite a few that are purely within the realm of biology or purely within the realm of computer science or engineering…Especially computer science, learning those kinds of skills, like bioinformatics, it's really hard to classify. Is that computer science? Is that biology? People on either end of that, in either discipline might not call their work interdisciplinary.

Clearly what constitutes IDR is somewhat dependent upon perception. Gerald shared a similar thought when he commented,

> I respect and appreciate all of my colleagues who do a lot of work at the DNA level [in biology] but that's not where I do my work so while I have no current collaborations with people doing the genetics behind some of the morphological things that I study, I certainly see opportunity for those collaborations and in my mind, even though we're all biologists, I would consider that interdisciplinary.

Edmund addressed the need for a broader definition of IDR further when he commented, "I think interdisciplinary research can mean a lot of different things to different people" suggesting that a single or universal definition may not be feasible. Caroline shared a similar thought when she said, "When I go to an evolution meeting they all say I'm a developmental biologist. When I go to a development meeting, they all say I'm an evolutionary biologist. Sometimes I'm like, maybe I don't fit in anywhere." This example highlights the importance of language or vocabulary in the life sciences research community. The language used by life science researchers reveals how their disciplinary knowledge bases are multiple and how such bases can even be divided into sub-disciplines within their disciplines. In pursuit of IDR, researchers must recognize and reconcile the resultant differences, a process that is unique to this type of work.

Operationalization of IDR – Selecting Collaborators

As noted earlier, when considering how life scientists operationalize IDR, we found that three themes were present in our data: (1) Collaborators should be selected intentionally, (2) Differences in languages must be reconciled, and (3) Actual and frequent collaboration is required.

Most of the participants in our study described themselves as intentional when asked to describe how they build an IDR research team or select collaborators, though their selection criteria varied widely. Edmund described his decision-making process for selecting team members relative to a new research project when he commented,

> Ideas here actually came from economics and sociology and not from microbiology. Those are not areas that I had been trained in as a microbiologist. We actually had to reach out to people who had different types of training to get that kind of input.

In this case, the collaborators were intentionally pursued based on their knowledge domains. Gerald reported that he uses criteria similarly based on participant expertise when reviewing his process.

> Perhaps one way to think about it would be through my experience working with individuals at a level where collaboration with the other discipline base on the table is something that I would not be capable of doing or bringing to the table. So skill sets, techniques, things that maybe I could figure it out with a sabbatical or enough time to work it out but…things that are fundamental to a project. So, computer scientists are able do some coordinating and a bit of a hacking, and do just enough to get by. When I work with computer

> scientists and engineers, at a much higher level, they are able to bring an approach to the table that I or no one in my field could have brought to the table, and it really advances the project… they're bringing their expertise skill set to the project in a way that we couldn't do on our own.

Identifying and selecting collaborators based on knowledge or skill set was identified as critical by five of the participants including Anna who shared the importance of selecting collaborators well versed in different methods:

> One of the simplest ways to select collaborators is based on methods, using methods outside of your discipline. I think it tends to be more collaborative by necessity, which I see as a bonus. It's good to bring together different perspectives. You're gonna do better science that way. It requires more work. You often don't have the background in your question that you would if you were just coming purely out of your narrow discipline. But I think it's all positive.

Selecting collaborators based on knowledge or skill set was recommended by Elizabeth too:

> When picking collaborators, you want to make sure you pick people who are very, very good at what they do. And who have expertise that complements your own. It's sort of silly to reinvent wheels with the same expertise represented multiple times.

Not all collaborator selection criteria shared by participants were based on expertise. For example, while he agreed expertise was important, Albert also emphasized the importance of personal relationships when he said,

> I've worked with [this colleague] on many different projects and he knows a lot about game playing in addition to evolutionary biology and his recent work is [more on the] education side of things… Based on all of these different projects, and I could have picked various projects with various different people but I tend to pick collaborators or people who I would end up talking with anyway because of [our involvement in the STC].

Albert selected collaborators based on whom he enjoys working as well as what knowledge they have relative to the project at hand. And other participants also acknowledged "Albertian" factors used in making selection decisions such as friendship, respect, and simply enjoying their collaborators. Dennis spoke rather bluntly when responding to the questions about how he selects collaborators when he said,

> Number one, I have to like the person. Most of the projects that I've gotten into I did because I enjoyed the company of the person I'm

> doing them with. It's not having to do with the subject matter or the methodology, it's just this is someone I want to work with.

This comment highlights the subjectivity with which some collaborations are undertaken.

Others spoke of the role the pragmatics of grantsmanship can play – with collaborators preparing a proposal trying to please prospective funders as they choose members of their teams. Elizabeth addressed the matter further discussing the matter of gender in the collaboration selection process when she said,

> Cynically, they needed a woman, honestly. So, they approached me, but when I heard about it I thought...we had all, admittedly, worked together on a previous big proposal that went to the military and didn't get funded so we'd all had this background talking to one another. There's a lot of people they could have asked to be co-PIs on this that were probably better suited for it than I am.

Elizabeth's comment suggests that her gender was in fact the driving reason why she was asked to be a collaborator even though others were perhaps more qualified in terms of expertise. Other study participants also acknowledged the role of the pragmatic in the selection of collaborators as when Albert commented,

> I was just applying to a NSF grant and we needed to get a biology collaborator just to check that box. That's more of a strategic decision as opposed to, "do we necessarily feel we need that person for being able to conduct the research now?"

It is clear, then, that collaborators are not always selected based on functional expertise as there often are a number of other criteria for collaborator selection operative. The only commonality in most of the comments we collected is that most partnerships were formed intentionally.

In some cases, however, our participants reported that collaborations simply happened as a result of being in the same place at the same time with someone with similar interests. This experience was shared by Marie who said,

> For me, [collaboration] really kind of just happened by talking to people and it's actually always come up in thinking about ways we can put in multi-lab and multi-investigator grants, the big project grants. And so, again, getting together, trying to identify common interests and how we could work together to generate a project. And so yeah, it's usually started from a brainstorming session of people that show up.

Reports like Marie's of this kind of experience recognize the importance

of in-person interactions, a point that was shared by a number of other participants. Dennis mentioned that he typically identifies collaborators

> Over beer, sometimes over whiskey. It is informal settings where you're chatting with someone and asking them what they do. You can usually tell if someone's really excited about what they're doing, and they're willing to describe it to you even though you don't have the training they do. It's often someone that you want to work with.

So get-togethers in which people discover they share similar research interests is another way collaborations are formed even though they are not necessarily being sought after or expected at the time. Anna shared a similar experience when she reported,

> Honestly, it was all serendipitous, every one of my collaborations. When I first started working with my chemistry collaborators first, during my postdoc, they had done a quick little throwaway study with another grad student in the lab. He wasn't going to pursue it, but it triggered something that I was interested in, and I said, "Oh, can we do some more studies on this – would you be open to it?"

Of course, such serendipitous informal meetings often happen at formal meetings. Edmund mentioned, "I've come to know a lot of people over time. In part, it's by going to meetings that have not been [in] a field of what I normally study so that I get to meet new investigators and see the sorts of things that they're interested in." Our study thus reveals that although most of our participants' collaborations were formed intentionally, more organic formation of collaborations via casual interaction was not uncommon.

Bridging Differences in Vocabulary

Participants were asked how they have operationalized IDR, a question that prompted participants to highlights the importance of developing common language. Organizing research that draws on multiple disciplines and knowledge domains can be especially challenging from a dialogic standpoint. For this reason, multiple scholars in our study included considerations of vocabulary when articulating how they operationalize IDR. Albert addressed thoughts he has about this issue directly when he said,

> I think we've definitely had terminology issues, so there is definitely that sort of collision that happens where we think we're vehemently disagreeing and then we realize we're using words in different ways and realize we are in agreement. And for disciplinary

> people, it's the translation of the ideas into a vocabulary that they'll understand [that] gets them excited and makes them want to reach out to find out more.

Reconciling disciplinary languages to ask and answer questions is critical to IDR because this kind of research often requires scholars to go outside disciplinary boundaries, including disciplinary vocabularies. Michael also considered the role of languages and IDR when discussing his own educational/disciplinary background:

> I would kind of go back to my background [because] the courses I am asked to teach [are] because of my background…[IDR] is people with deep backgrounds that are quite distinct and different due to their education, I guess. That's where there's often just this huge difference in your background where you talk about the same things in very different ways because of the languages you learned. So, that's what I think of in disciplines and [interdisciplinarity] where it's just people with these deep backgrounds that are quite distinct and different due to their education, I guess. Their classroom education, usually.

Unsurprisingly, these differences appear to be most evident when scholars use language to describe and address problems that permeate multiple fields and hence call for IDR.

Gerald also focused on the challenge related to language in his experience operationalizing IDR.

> I still think it exists – a disconnect between [problems in] communication between fields, [for example] between engineers and biologists[;] while they collaborate together, [they] spend a lot of time talking past one another. So they might be using the same language that means different things, or talking about the same things using different language and I have found it really quite valuable to understand the perspective of an engineer by spending time in those labs in that department, to know how to interpret and communicate, and that has been very beneficial for me in my career when I have worked with engineers, to be able to have a conversation [in which] we're on the same page.

IDR requires scholars to make bridges to those representing other disciplines. Our participants often stated that, to that end, a common language must be developed, understood, and utilized. Marie discussed the importance of reconciling language differences when she said,

> When you start the project, and after, say, after you've already identified someone that you're working with from another

> discipline, [you're] kind of learning each other's language a little bit and understanding what we actually do. When my collaborator from another discipline is using a certain word, and I'm using it, and we're using it in different ways, I think it's important to get that lingo down from the beginning and it's important to not assume that you are on the same page.

Thus, while participants agreed that awareness of different educational backgrounds, literature, approaches, and methods is critical to successful IDR, the reconciliation of different vocabularies may be the most critical of all. The recognition of the need to develop common language and adopt a common understanding of terms that may have different disciplinary-based meanings is a key feature in our participants' comments on how IDR scholars operationalize IDR research.

Frequent and Authentic Collaboration is Required

As our conversations with participants revealed, important characteristics that distinguish successful IDR are frequency and authenticity of the interaction involved. When Michael was asked about how IDR work should be conducted he said,

> I think IDR is a buzzword. That it's something that everybody wants to be and do, but it's not easy...it takes a real investment to do well, I would say. A long-term kind of interaction between two people. So done poorly, it's just assembling some team to check a bunch of boxes and say that you're doing different things. How like determining the team, first of all, is a really important thing because there's a lot of issues of kind of, first, communication, that you have to establish, right? We already have kind of these different languages. Some people think certain things are interesting or not interesting depending on their discipline. You know, something could be the best thing ever in one discipline, but completely boring in another discipline. Or it takes a little bit longer to decide on the goals for this reason as well. What is the actual goal, what is even publishable or interesting, and these types of discussions can be a challenge in these situations.

As Michael suggests, successful IDR work requires frequent dialogue, preferably in the form of actual conversations to address and resolve challenges that often arise out of fundamental differences in the disciplines of the collaborators involved. Elizabeth shared similar views when she responded to the question of how IDR collaborations tend to work, though

she emphasized the need for good leadership as well as real communication:

> Very variable; really depends on the nature of the leader and if there's somebody who's trying to put words in your mouth or trying to be a Nazi at the head of the effort, it's just going to fail. It is a really good idea in every collaboration to talk about things up front and say, "Okay. Now, if you do this, and you do this, and you do this, how are we going to divide the labor, and how are we going to divide the credit? Where are the data going to end up?"...it's just a lot of practical stuff that comes up that can really get in the way if you don't think about it ahead of time. This type of work requires actual collaboration.

Even beginning much less completing IDR-related projects requires a great deal of such "actual collaboration," a factor that differentiates this work from disciplinary-based projects. Stephen shared similar sentiments when he commented on the extra expenditures of effort required by participants in IDR-related projects and their leaders:

> I think there's a common element to how things are interdisciplinary, multi-disciplinary, or transdisciplinary, which is, is there a real investment into the different knowledge disciplines. So I guess the two major elements [to IDR] are real investment in multiple disciplines, and serious effort. I think that things fall flat when that second step doesn't happen. … [Leaders can see that it does happen by using] responsiveness, keeping people aware of what the challenges are, and what the needs are. And managing expectations. So, I mean, [when I am leading a project] I certainly try to build an awareness of what the goals are. I certainly try to invite stakeholders to get involved, so they can see what… the challenges are and objectives are. I think I have to pay extra attention to professionalism. People call them soft skills, but that's not a recommended phrasing nowadays. Professional development skills. That lines up a lot into [organizing an IDR team]. I say start to finish. I think that...I mean, I think that's an element that relates where everybody is positioned for doing things. I think it's been difficult to set up a team here, or be involved in teams where people are not...broadly involved across all elements of a project.

This description highlights that there is a real need for those leading IDR to invest in and understand the different disciplines that are involved in the research project – and to help others to do the same. Marie also emphasized how important and different communication is for IDR research than non-IDR research when she said,

> Some [collaborations] worked well and some haven't, and I guess one thing maybe that, I don't know, this kind of has to do with leading I guess, is that…I think where there's groups where people, there's a clear leader from each of the disciplines, but they're working together, but they've....So say it's two people, like me and my physics collaborator. I'm leading the biology side, he's leading the physics side, and then we meet with a group with all kinds of other people that are working on these projects. But it really requires an investment [from] both of us to move our sides of the project forward and to interact….You've gotta have someone in a leadership role for both disciplines or multiple disciplines that are motivated to carry the project forward. So it's a lot of communication and just knowing how we can keep moving the project forward without any of those kind of lags, where they can't do their modeling if we don't get them the data. Or if we can't get them the data, more data, if they haven't analyzed it. And so yeah, I think it's just a lot of communication and making sure that all aspects are moving forward as efficiently as they can.

Within IDR collaborations it appears that a strong leader who clearly communicates with and motivates and monitors the team is essential for IDR collaboration success. The IDR life scientists we interviewed shared how critical real collaboration (under strong leadership) is at each stage of the research process from the literature review, to the selection and development of the methods to be used, to the collection of data, to the interpretation of the findings. It is no wonder that they consider IDR more challenging than discipline-specific work.

IDR Broadens Understanding and Produces Great Scholarly Rewards

Our life scientists also shared that they value IDR in spite of the challenges involved because it broadens understanding of a given topic and produces better solutions to complex problems than discipline-specific research. Although they were quick to mention that IDR work is not valued equally across departments or universities or indeed the whole of academe in comparison to disciplinary work, these scientists found that the value they themselves place on this work outweighs the problem of others' negative perceptions. Elizabeth spoke to this directly:

> To me, [IDR] is more interesting [because] interdisciplinary work has a broader appeal. That's where the frontiers of our understanding are. You are either working at the interface between disciplines or

> drawing on the tools from one discipline to attack problems that have plagued the other discipline for a long time….Disciplinary work tends to be more narrow and focused and I think interests a narrower array of readers….[IDR] has been a very powerful mechanism for letting us go back and forth in generating new hypotheses to test. In those respects, it's really been fabulous…. It's broadened my understanding, from just bringing psychology together with biology, or physiology together with behavior, which I've been doing all along, now we're talking about modeling those things in a machine world that can just make evolution happen so fast. You can suddenly literally see things changing before your eyes as you go through thousands or hundreds of thousands of generations in silico. That's been an eye-opener.

Elizabeth articulated how she has found IDR work different from discipline-specific work in that it broadens expectations from a research and publishing standpoint and enables those involved to make progress more quickly than they otherwise would.

When Edmund was asked what he values about IDR work he was quick to report that he values "the non-overlapping areas of expertise required to advance a research question that cannot be answered independently by any one of those fields." He also went on to compare IDR work with non-IDR work saying,

> There are always limitations to the way that any one field designs its experiments and any one field can interpret its data…the range of questions that you can answer and the restrictions on the latitude for the interpretation are different. I think that if you can ask an interdisciplinary question that is germane to multiple areas of investigation, you have the potential benefit of being able to interpret with a broader range of applicability than you would have had if you just stuck to one field….Interdisciplinary work expands our horizons. We like to think that it informs other fields. I think the most notable thing to me is that when we've been successful…it's basically opened up a whole new line of investigation, not just for us but for the field…when you succeed with an interdisciplinary project, you open additional lines of investigation both within our discipline [and within] the other [disciplines involved].

This comment really highlights a belief shared by a majority of the participants in our study, namely that IDR enhances the ability of researchers to answer questions while promoting innovation and discovery. It not only broadens the understanding of the topic under study, but encourages further work

that may yield further applicable knowledge. Along these lines, Caroline reported,

> I really think the value [of IDR] is just looking at problems in a different way. It's kind of like the little parable of the elephant. Some people are looking at the tail. Some people are looking at the head. Some people are looking at the trunk. They all have a different idea. I think we all want to do that big picture. Everyone always talks about the big picture, but we don't realize what kind of thing we're looking through. We're getting this small glimpse of things.

This analogy portrays the limits felt by life scientists working within their disciplines. When life scientists engage in IDR, they are able to see a more complete picture of a problem under study and research it more comprehensively.

Another participant in our study described the value of IDR by emphasizing the quality of the "solutions" to problems the research produces. Albert commented,

> A solution is rated based off of how well it solves the problem and how different it is from other things that solve a problem – [IDR is] a more powerful approach because you're taking many different techniques that would be considered to be from different disciplines and using them all to solve a problem.

IDR harnesses the knowledge of experts in different fields, an approach that ultimately yields more holistic solutions to challenging problems. Gerald agreed that IDR counters the tendency of disciplinary researchers to focus too narrowly to achieve holistic solutions:

> The value of interdisciplinary research as I sometimes put it, and this is my understanding, as to whether we're vested into it or not, I think we tend to get locked into our point of views and our disciplinary dogma of how things are; and it's not until somebody comes along with perspective and says, "Why? Why does it have to be that way?" It asks where you really have the opportunity to make advances and change paradigms by really looking outside the box and thinking about what makes the older ways.

IDR encourages researchers to think with other experts in ways outside of the bounds of their individual disciplines, creating the opportunity to advance paradigms. IDR creates an environment that allows the questioning of foundational disciplinary beliefs that may not often be questioned to reach new levels of understanding.

Researchers value IDR not only because it broadens the understanding

of problems and improves suggestions for solutions to those problems, but also because it expedites the process through which discoveries are made and solutions propounded. Several participants in our study commented on the expedited pace with which work is done as a result of the collaborative process involved. Caroline commented,

> Ten or even twenty years ago, I never would have thought I'd be doing something like that. That is pie in the sky or something like that. Now, it's just amazing the kind of tools that [those of us doing IDR] have. It's funny because frequently evolutionary biologists, certainly when we started sequencing genomes, Darwin knew this or Darwin this or that. I was like, I think Darwin would be out there sequencing these genomes as fast as I am. You know? I think he'd be like, I wanna know how things work, man. I gotta use the tools. What I used to tell some of my friends is if I want to get from Seattle to New York, I'm going to take a jet plane. That's what genomics does for me. If you want to take a wagon train, you can take a wagon train. Not the same journey. Not going to get there as fast. I'm like, if I just wanna go from Seattle to New York, I'm taking a jet plane. Going to get there as fast as I can. I feel like that's what genomics and computational biology does for you. It's your jet plane so you can get places that we never expected to get.

This quote showcases Caroline's belief that IDR enables life scientists to get to places they never expected to reach doing work on their own within their individual disciplines – and get there fast.

Other life scientist scholars in our study were also adamant that IDR produces greater scholarly rewards by expediting discovery and ultimately accelerating knowledge production in the multiple fields involved. Anna shared such a belief when recounting a past experience:

> So I analyze the chemistry data to see how it relates to the behavior, and I can say, "Oh, look. This cool thing happened," and I don't know what this compound is, but my chemist will say, "Oh, my God. That's so amazing because this does that in plants." My microbiologist collaborator will say, "Well, this is really common in...." So there's just knowledge background that I don't have that would take me a lot of work to turn up things that people just know in other fields. I don't have that kind of, I guess, tribal knowledge of things….I feel like it's all kind of notable, I mean, just these discoveries of finding out that something that meant nothing to you is hugely important to somebody else. That actually happens a lot in my [ID] research with all my studies. There's always something

> that pops up and changes what a field thought about something.

The value of IDR is not only in the way it enables researchers with many kinds of expertise to deal with particular questions, but also in the way it allows advancement in the multiple fields involved. IDR has certainly led to discoveries that might have never occurred without these types of research partnerships. Stephen also claimed that IDR work not only allows but also accelerates discovery when he reported,

> I think interdisciplinary work has been why science has accelerated in areas such as molecular biology and energy physics, because we are comparing the imaginary world of analysis to real findings… Interdisciplinary work is to further connect things together so that they accelerate and have more momentum. All the great science happens with interdisciplinary work.

Accelerating knowledge production is a key reason the life scientists we studied value IDR. Stephen went on to share, "I think you'll be able to ask bigger questions, and attempt to solve bigger problems [as a result of IDR]." During a time when life scientists and other STEM scholars from around the world are working on some of the most challenging and complex research questions facing society, our close study of some of their representatives suggests they understand that IDR work is one avenue worthy of their collective time and effort in spite of the considerable challenges involved.

Discussion

Until now, little has been known about how researchers, especially researchers who are learning to do IDR while doing IDR, as is so often the case, conceptualize IDR, but the present study highlights key views shared by life scientists engaged in such work. We have known that the learning curve for those doing such work is steep (Leahey et al., 2017) and that conducting such research is complex, and our study confirms that (Cumming & Kreisler, 2008; Ledford, 2015). But it has also revealed a good deal more, shedding light on how life scientists conceptualize, operationalize, and value interdisciplinary research.

Conceptualizing IDR: Implications

While scientists from across disciplines and knowledge domains have been called to work together to solve grand challenges facing society (Disis & Slattery, 2010; National Academies of Science, 2005; Wuchty et al., 2007), there has been limited study of how they themselves conceptualize or

characterize interdisciplinary research. The life scientists we studied said that one of the salient attributes of IDR is the integration of insights from different types of expertise. They supported the notion that without IDR, researchers tend to view their world through disciplinary lenses whose narrower focus determines how problems are studied, which methods are selected for use, and how findings are interpreted. For research to be considered IDR, it must leverage multiple ways of knowing, requiring interaction among colleagues from different disciplinary backgrounds to address the complex questions under consideration. According to the life scientists we studied, for work to be considered IDR, it must include the discussion and reconciliation of the different perspectives such colleagues bring. Further, results from this study suggest that this interaction can happen among those representing the sub-disciplines of disciplines as well as among those representing disciplines.

Operationalizing IDR: Implications

While collaborators were usually selected intentionally by the life scientists included in this study, they were not often selected based on any single dominant factor. Of course, whatever selection criteria are used, IDR does involve collaborators from different disciplines (or sub-disciplines). And that creates challenges. The life science scholars we studied acknowledged that barriers are often present between collaborators of different disciplines (or sub-disciplines) when they are attempting to outline and pursue research projects, and even interpret research findings. These communication barriers required our life science researchers to develop a common language in order to advance their work. Although other scholars have discussed the issues of language in IDR, the present work confirms the importance of developing shared language (Norton, 2005). The participants in our study made the further point that collaborative research needs to be done in common or conjunction with one another. They noted that if IDR work is to get done at all and done well, the research cannot simply be divided and delegated to different members who work separately before putting the final product together at the end. On the contrary, IDR requires frequent and authentic collaboration – that is, actual interaction – so all the team members can consider, converse, and reconcile different disciplinary-based perspectives to further the work.

Valuing IDR: Implications

Our research has shown that life scientists value IDR because the collaborations not only broaden understanding of the problem under study, increasing the likelihood of a good solution to the problem, but also expedite the rate at which progress towards the solution of the problem is made. Each person in a collaboration brings different expertise to the project, giving those in the group access to methodologies and knowledge they have not used before as well as access to support from the other participants' departments and institutions. Opportunities for intermingling among researchers and research communities can lead to new collaborations too, potentially fostering more cross-disciplinary explorations. In sum, IDR advances science (as it does other fields of knowledge) through the collaboration of people with different perspectives and expertise.

Conclusion

Given that the advancement of science and knowledge itself comes from the collaboration of people with different perspectives and expertise, it is more important than ever for institutions to reduce and ideally remove barriers related to interdisciplinary research. In many cases, barriers related to career status, values, disciplinary culture, and reward structures have inhibited successful IDR research. In order to promote IDR work, it is important for universities (and the departments within them) and funding agencies to acknowledge and reward researchers for working and publishing with researchers in disciplines other than their own. The data presented here also reveal or at least confirm that many of those who do IDR have not emerged from an interdisciplinary background – that is, have not had the training in ID work that undergraduate and/or graduate programs in interdisciplinary studies might have provided them. Nor have they, since beginning their post-graduate careers, had the benefit of institutions or departments who were willing to support their IDR endeavors by supporting their attempts to somehow garner the expertise in IDR they did not garner in their degree programs. For IDR scholars to function at an optimal level they should attend interdisciplinary conferences, read interdisciplinary journals, and have consultations with other interdisciplinary scholars, thus building up a strong IDR knowledge base that will let them better manage their work. Certainly knowing how to do it before doing it – instead of learning how to do it while doing it – would be a big advantage. Ultimately, we believe the results of our study should guide institutional leaders in providing their faculty that big advantage, suggesting how they might better support faculty who are pursuing IDR.

Biographical Notes: Alexander C. Gardner, PhD, is a human resources, adult learning, and workforce development scholar and practitioner. He is a graduate of Kalamazoo College, and holds a master's degree from Michigan State University's College of Human Resources and Labor Relations and a PhD in Higher, Adult and Lifelong Education from Michigan State University. Alex's academic research interests include individual competency development, network improvement communities, workforce readiness, higher education policy, and postsecondary labor market outcomes. He may be contacted at gardn179@msu.edu.

Benjamin Espinoza, MA, is a PhD candidate in Higher, Adult, and Lifelong Education (HALE) at Michigan State University. In addition, he is pursuing a graduate certificate in Chicanx/Latinx Studies. He currently works for the Michigan State Honors College conducting research in student retention and success. Previously, he worked for the Department of Educational Administration at Michigan State as a research assistant, working in the fields of adult learning, emotional labor, and interdisciplinary collaboration among STEM faculty. His research interests include academic labor, the experiences of racially minoritized students in higher education, student success, the intersection between race and religion in higher education, qualitative research methods, organizational leadership, and religious institutions. Ben is fortunate to have served on a number of boards, including the boards of the Children's Spirituality Summit and the Association of Youth Ministry Educators, two leading organizations focused on studying the spirituality of young people. He serves as the senior associate editor for *The Journal of Youth Ministry*, and has extensive work serving in non-profits. He may be reached at espino64@msu.edu.

Chelsea Noble, MA, is a PhD student in the Higher, Adult, and Lifelong Education program at Michigan State University. Her current areas of research include interdisciplinary research, multi-institutional collaborations, and diversity, equity, and inclusion initiatives. She holds an MA in Higher Education from the University of Michigan and a BA in French from Bowdoin College. She may be reached at nobleche@msu.edu.

Marilyn Amey is a professor of Higher, Adult, and Lifelong Education and chairperson of the Department of Educational Administration at Michigan State University. In 2017, she was appointed as the Dr. Mildred B. Erickson Distinguished Chair in Higher, Adult, and Lifelong Education. She studies educational partnerships, particularly those of community colleges, leadership, including how leaders learn, post-secondary governance and administration, and faculty concerns, including interdisciplinary academic work. Her current work focuses on education partnerships including a multi-year evaluation of a multi-institutional interdisciplinary consortium and factors affecting student transfer and degree attainment. She may be reached at amey@msu.edu.

Patricia Farrell-Cole, PhD, specializes in organizational development, transformation, policy, and leadership. She holds a master's degree in Organizational and Adult Learning from the University of New Mexico and a PhD in Higher, Adult,

and Lifelong Education from Michigan State University. Her work in academia has included evaluating programs and organizations, directing associations, serving as a collaborator and leader, and advising and teaching students. Her evaluation and research work has focused on programs, organizational effectiveness and impact, state and federal policies, student access and success, and multi-institutional work. For the past 10 years, she has been the co-evaluator for studying the organizational effectiveness and impact of an NSF-funded Science and Technology Center. She may be reached at plfarrellmsu@gmail.com.

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Appendix

Questions

1. In the STC database, you are listed as a _____. Being from education, please talk about what it means to be in this field/discipline and how you would describe your current research initiatives.
2. We are interested in hearing you talk about interdisciplinary research. From your perspective, what is interdisciplinary research?
3. In what ways does interdisciplinary research differ (if at all) from discipline-specific research?
    A. From your perspective, can you describe the ways in which you believe disciplines inform one another during the course of an interdisciplinary research project?
4. How do you know when you have crossed the boundary to interdisciplinary research?
    A. What makes it interdisciplinary research?
    B. What is the threshold between disciplinary and interdisciplinary research?
5. What do you need to take into account when doing IDR projects?
    A. How does your role as a leader or team member impact how you approach IDR work?
    B. How do you go about selecting your collaborators and why?
    C. How did you work with your collaborators regarding disciplinary norms, methods, and approaches?
    D. How are responsibilities distributed for certain aspects of the study? [e.g., specific aims/goals, research design, data analysis, dissemination (writing/presenting)]
    E. How do you determine your outputs or publications with your collaborators?
6. When you are making decisions, how is your process and what you take into account the same for or different from discipline-specific research?
7. Based on your experiences with interdisciplinary research studies, what was most notable about those experiences?
8. What do you think the value is of interdisciplinary research?
9. Why is there a need *for you* to do IDR work?
10. Is there anything else about interdisciplinary research that you think we should know?