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Do-it-Yourself (DiY) Science: The proliferation, relevance, and concerns

Abstract

Do-it-Yourself (DiY) science and their 'citizen laboratories' are flourishing as they continue to attract unprecedented number of volunteers, communities, groups, and venture capitalists. However, the evidence on why DiY science is proliferating remains scattered and the dominant narratives around DiY practices consist of multiple understandings, beliefs and expectations. In this paper, we attempt to map the ever-expanding landscape of the DiY science movement by surveying studies on DiY science practices to highlight the forces fostering the phenomenon. We highlight the relevance of DiY science activities to its practitioners and the general public, its positive promise for the birthing of innovative products, as well as the potential risk associated with the phenomenon. We conclude by delineating potential ways to strengthening the operational capacity of DiY community laboratories so as to harness maximum benefits from their operations.

Keywords: DiY science, community science hubs, open-source movement, innovation

Introduction

Do-it-Yourself (DiY) science has come to represent the activities of independent community-based science research hubs, often set up and managed by scientists, science enthusiasts, volunteers, communities, and groups with genuine interest in science to learn, experiment, and get involve with the world and practice of science, technology and innovation. Echoing the ethos of Galilean and Newtonian times where the raw pursuit of knowledge drove science researchers (Kantorovich, 1993; Gallopin et al, 2001), mostly untethered to scholarly affiliations, to scientific experimentations of theories, increasing consensus is forming that DiY science, unembedded in rigid hierarchies, is opening 'an avenue back into the scientific research experience for the engaged layperson' (Scheifele and Burkett, 2016, p.84). Challenging the near monopoly of traditional universities and research institutions as the fundamental locus for practicing science (Downes et al., 2013; Halfacree, 2004), DiY science practices, in recent years, have increased exponentially due to the availability of open-source-garage-cheap equipment, advancements in information technology and web-based communities (Fox, 2014).

The practice in recent times is not only is attracting a significant number of science enthusiasts and talent located within and beyond the borders of universities and traditional research institutions. It has also caught the public imagination and the attention of governments, policymakers and academics, due to the potential it has come to hold for synthetic biology (Landrain et al., 2013), for democratisation of innovation (Von Hippel, 2005), for fostering a citizen science, for demystification of science, and for its educational, economic and socio-cultural value (Wolinsky, 2009; Wylie et al., 2014; Meyer, 2013, 2014). Predominantly funded by philanthropic organisations and members of the general public (Scheifele and Burkett, 2016), it possess certain neoliberal epistemological characteristics - interdisciplinary, design and use of cost effective tools and equipment, open source and open science innovation (Seyfried et al., 2014; Rognoli et al., 2015) - which can serve as a springboard for innovation and scientific progress at the grass root level (Ferretti, 2019; De Roeck et al., 2012). In this regard, the socio-economic and cultural significance of DiY science cannot be overemphasised. For some commentators, DiYbio and e-waste hacking, for example, is a way of questioning closures and precarious material conditions produced by post-industrial capitalism in the age of the internet (Delgado and Callén, 2017); to others DIY science, through 'craft production and consumption' challenges conventional producer-consumer relations (Watson and Shove, 2008). Also, some works suggest that the playful and imaginative nature of Making and Tinkering is beginning to dismantle the notion of 'science is for scientist' (Bevan, 2017, p.14). Elsewhere Meyer (2012) posits that DiY science constitutes 'a material re-distribution, a democratisation and an alternative to established technoscience'.

Despite its praiseworthy attributes the dominant narratives around DiY consist of multiple understandings, beliefs and expectations, entangling different views on themes such as innovations, ethics, new technologies, education, employment and risk assessment (Ferretti, 2019). As promising as DiYbio, for example, can be, studies have argued that its largely unregulated feature implies risks for its practitioners, human health and the environment. (Schmidt, 2008; Gorman, 2011). Thus a welter of security concerns about DiY forms and arenas of scientific experimentation are raised. Among them others have posited that allowing amateurs and novices to tinker with scientific experiments outside of traditional institutions could be a potential threat to global security (Schmidt, 2008). The 'de-skilling'[1] implied in synthetic biology may encourage the design of criminal weapons by, for example, 'DiY malefactors' (Gorman, 2011), see also (Tucker, 2011). Also with regards to synthetic biology, Ahteensuu (2017) identifies that the spread of the required know-how, and the improved availability of the techniques, instruments and biological parts raises biosecurity and safety risks. This may be due in part to

1 A gradual decline in the amount of tacit knowledge required to master a technology (Tucker, 2011, p.69)

the fact that DiY participants, being mostly young scientists and non-scientists, see for example the demographic profile of the research participants in (Kwon and Lee, 2017), may not always be in tune with biosafety procedures (Ahteensuu and Blockus, 2016). In sum the divergent literature contains many examples of how DiY science could serve as a potential means to pushing scientific frontiers on the one hand. On the other hand, some works highlight the perils of hacking, underlying security and ethical implications of DiY practices.

It is however not the aim of this study to comprehensively cover all the historical and developmental aspects of DiY or the maker movement per se. To seek to achieve such an aim would require far more space than is available here. Besides DiY/maker movement embodies so many indicative themes of relevance that its pursuit to the core could make its treatment quite intractable[2]. Nevertheless, a useful purpose is served by seeking to provide an integrative review of the existing canon of works. The aim of our survey therefore is twofold: first we seek to provide a helpful guide to recent literature on the DiY landscape for those interested in the broader open science movement but for whom the DiY topic is new. This aim is informed by the fact that most of the DiY narratives carried especially by the media appear to be anecdotal and speculative. Although some empirical and conceptual studies have addressed these DiY science 'hypes and horrors' (Seyfried et al., 2014) and 'myths' (Grushkin et al., 2013; Jefferson et al., 2014) usually presented by the media, relatively little has been written regarding reviews. Thus, our second aim is to contribute to the dynamism concerning the expansion of the DiY movement by pulling together into a single document and discussion the relevant but scattered aspects of the literature that highlight the determinant factors fuelling the flourishing of DiY science, the relevance of DiY practices, the positive promise of DiY for innovation, as well as the risk-factor discussions associated with the phenomena. By doing so we seek to provide a knowledge repertoire and thus guidance for policy making which can potentially improve the quality and effectiveness of policy measures targeted at the DiY science practice.

Our integrative review is structured as follows. First, we delineate our methodology underpinning our inquiry. Next we map what has come to represent DiY science, its resurgence, and relevance in contemporary. Following this, we delineate the ambivalence relationship between DiY science and institutionalised science after which we provide an overview of DiY science as a vehicle for the identification of opportunities for innovation. In the penultimate section, we revisit the concerns frequently raised about DiY science as an alternative model for traditional science research, and conclude with some implications of DiY science for contemporary science, technology, and innovation policy.

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2 For example, a relevant branch of DiY enquiry not examined in the article is the nexus between DiY laboratories and environmental sustainability.

Methodology

In surveying the rapidly growing literature on DiY science, we empirically orient ourselves along the literature synthesis approach as described by (Webster and Watson, 2002). In this case, we seek to analyse and synthesise the DiY/Maker movement literature along our research aims and then present a conceptual model. In doing this, we first identified relevant studies based on our review's primary objective of distilling evidence on why DiY science is proliferating, its relevance, and the risk framing narrative associated with the phenomenon. Here we limited the search to works in English representing both the white literature (peer-reviewed publications in scientific databases – Google scholar and Web of science) and the grey literature (online reports, conference papers etc).

In search of the white literature in the scientific databases, the main keyword search included the search strings 'DiY science', 'Maker movement' 'the importance of DiY science', 'DiY and innovation', 'DiY and biosecurity', 'DiY and biosafety'. We particularly focused on works published from 2008 – 2019. This is because although DiY practices span a long history, the creation of the association of the DiYbio community in Boston in 2008, marks a watershed moment in galvanising a recent upsurge in DiY scientific practices (Meyer, 2014). Because published works is generally interlinked to a large degree – one 'stem' paper leading to other 'branches' of papers we were able to find more relevant works. As references built up we noted some of the works were more central and carried a large number of citations. Such papers were considered as seminal works (our criteria were papers published up to 2019 with 50 or more citations). However, because some major DiY studies appear not to be published in the traditional academic journals (signifying the ethos of DiY science which opposes the highly bureaucratic nature of institutionalised science), our search for literature was further expanded through the snowballing technique i.e. by checking the references of the articles yielded by the initial search.

Not surprisingly we found that the studies geographically focus on Europe, USA and Asia which reflect the fact that the vast majority of DiY practices and their community laboratories are located in these regions (DiYBio, 2019). Although broad section of the DiY movement literature was surveyed, we particularly focus on the seminal works that deal with DiY science and Making. In all thirty-three (n=32) seminal works captured in this study. Details of these seminal works are presented in the appendix

Results: Mapping DiY science

DiY science, generally referred to by a plethora of names such as Maker movement[3], Citizen science[4] see for example (Fiske et al., 2019), Hacking, (Tanenbaum et al., 2013), captures, definition-wise, the process initiated by individuals and groups, who out of curiosity, need or interest, tinker, hack, fix and recreate objects and systems using open-source equipment and aim to openly share results and findings in their networks (Nascimento et al., 2014; Ferretti, 2019). In practice the DiY movement concerns innovative forms of Making – the incorporation of high and low digital technologies into acts of designing and constructing physical, and sometimes virtual objects (Kim and Shin, 2016; Kwon and Lee, 2017; Baden et al., 2015; Kuznetsov and Paulos, 2010), embodying specific enterprises in, for example, biology (DiYbio) (Landrain et al., 2013; Grushkin et al., 2013; Meyer, 2013; Tachibani, 2011). The actors shaping DiY trajectories are sometimes referred to as 'Makers' (Kwon and Lee, 2017; Dougherty, 2012), and 'Citizen scientists' (Ahteensuu and Blockus, 2016; Haklay et al., 2018). The actors also include biohackers – biologists whose operations are characterised by a wider milieu of features which Ahteensuu and Blockus (2016, p.28) refer to as *agora science* (open access databases, sharing platforms, open participation to biological research without recourse to formal organisations), see also (Yetisen, 2018; Kelty, 2010; Delfanti, 2011). These DiY actors are not only amateurs, tech-enthusiasts and hobbyist but also an increasing number of professional scientists (Grushkin et al., 2013) who usually carry out their scientific engagements in the so called 'hackerspaces', 'hacklabs' or 'makerspaces' ie community-operated physical places usually outside of the institutionally established scientific locations including private locations, classrooms, museums, public libraries (Maxigas, 2012; Kera, 2012; Grushkin et al., 2013). Some of these actors also practice their DiY scientific engagements at home, what is usually referred to as 'kitchen biology' (Wolinsky, 2009) or 'garage biology' (Nature, 2010; Ledford, 2010). A quintessence of this home laboratory is the famous story of a private laboratory set up by Kay Aull, a PhD student at the University of California, San Francisco, see (Meyer, 2012; Wolinsky, 2009). However, most DiY practices take place in community labs and hackerspaces which include, for example La Paillasse (Paris), BiologiGaragen (Copenhagen), MadLab (Manchester), Genspace (New York), and Hackteria (Switzerland/Slovenia). These settings allow access to everyone, especially 'amateur scientists' (Alberti, 2001), regardless of their academic and socio-cultural background (Landrain et al., 2013). This is because the historical

3 According to Baden et al (2015), the 'Maker movement' is a technology-oriented offshoot of the traditional 'DiY' movement, typically denoting specific pursuits in electronics and related technologies. In this study both terms and concepts (DiY and Maker movement) are used interchangeably to encapsulate the DiY definition by (Nascimento et al., 2014) .

4 Citizen science also falls under the umbrella of DiY science. However the difference is that whereas DiY practices principally fall outside of activities of the traditional institutionalised science (universities and research institutions), citizen science practices usually involve active involvement of its actors in collaborative projects with institutionalised science, see for example (Ahteensuu and Blockus, 2016; Nascimento et al., 2014). Although some citizen science 'literature' is included in this review, we heavily rely on literature that focus on DiY science and the Maker Movement.

development of the practice is rooted in the long history of amateur science communities, which, according to Alberti (2001), constitute the frontline of the scientific industry.

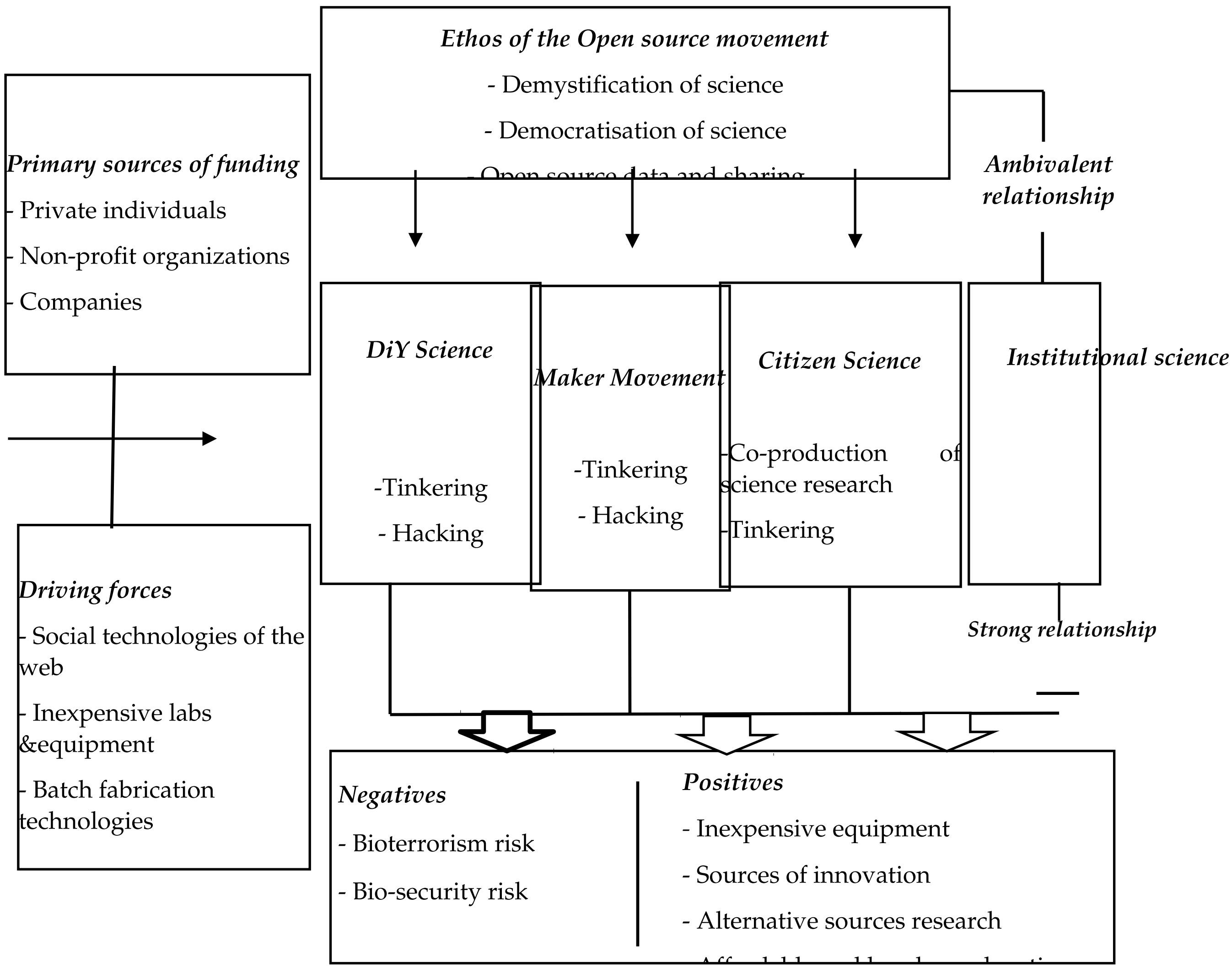

Figure 1: Do-it-Yourself (DiY) Science landscape

Our mapping suggests that DiY science is not just gaining traction around the world; it is also opening up the processes of science, technology, and innovation to the public (Hecker et al., 2018; Sleator, 2016). The practice, we argue, has a real potential to reducing the myths, the magic, and mistrust surrounding science by challenging the very idea of what constitutes science, and who can practice science. We present figure 1 as a simplified view of the emerging DiY science landscape, showing how the practice challenges the near monopoly of traditional universities and research institutions as the fundamental locus for practicing science, their proliferation, relevance, and potential concerns raised about these community based-laboratories, and their practice.

DiY: The flourish of a quiet revolution

As earlier stated, DiY is gaining global momentum with various factors explaining the rapid spread of the global movement. These include the rising suspicion with which science experts are being regarded by the general public, especially by DiY activists, and the gradual decline of public trust in science (Gauchat, 2012). As argued by Berditchevskaia et al. (2017), public trust in 'expert' knowledge is increasing eroding as a result of growing frustration with power hierarchies and systems that reinforce elitism. In the US, for example, many individuals continue to express deep seated concern about the way research has been politicised in order to entrench prejudiced ideological stance (Gauchat, 2012). A lot of revelations have also emerged pointing to high levels of corruption and manipulation of data in the various fields of science. The Editor-in-Chief of one of the leading science journals, *The Lancet*, for example, notes:

> The case against science is straightforward: much of the scientific literature, perhaps half, may simply be untrue...The apparent endemicity of bad research behaviour is alarming. In their quest for telling a compelling story, scientists too often sculpt data to fit their preferred theory of the world (Horton, 2015).

Thus as a way of rebelling against 'corrupt' science, and in the context of increased democratisation of knowledge, individuals are beginning to embrace the 'confirmation bias' by giving more weight to their personal accounts, and information shared within network of peers (Berditchevskaia et al., 2017). Also, with the traditional expert science leaving little to no room for public engagement in knowledge production (what social scientists sometimes refer to as the 'public deficit model') (Gauchat, 2012), more and more individuals are clinging to DiY sciennce as a way of helping to shape knowledge which sometimes directly have relevance on their life (Berditchevskaia et al., 2017).

In certain quarters, the proliferation of DiY science is seen as a reaction against the reductionist view of university scientists that scientific studies and research can only take place within the confines of the university (Griffiths, 2014). Other studies relate to the discussions by submitting that DiY science is gaining momentum because university research is slow to change direction especially at this period of rapid growth, innovation and development (Griffiths, 2014; de Lorenzo and Schmidt, 2017). DiYers can also be seen to be questioning the dogmas of the 'neoliberal science regime practices of professionalization and appropriation of knowledge' (Lave, 2012). For Delgado (2013) DiY can be viewed as a reaction against the bureaucratically and technically-over-mediated way of doing research in which expected results and repetitive assignments replace individual curiosity. In the context of job precarisation, the dominance of hierarchies and high pressure for publishing associated with the academic environment, which has meant few opportunities for young researchers, one alternative route of research has been the hacking of biology i.e. turning it into a low cost and creative technical practice that can be 'owned' by anyone (Delgado and Callén, 2017; Nicholson, 2012; de Lorenzo and Schmidt, 2017). In this sense the proliferation of DiY science has become a political and technical demonstration that one can go 'solo' (Dance, 2017), and that 'you' can also do it (Delgado and Callén, 2017). In sum DiY labs and communities are proliferating because they are providing important alternative research avenues for hundreds of scientists 'disillusioned with academia' (Dance, 2017). This is encapsulated in the study by Delgado, thus:

> To do a good hack ... there is no need to spend time in acquiring a PhD, in entering slow funding systems, in waiting for academic peer-reviewers and top journals to state what is valuable knowledge, and for an expert committee to say which research projects are worth carrying out. (Delgado, 2013, p.69).

Another keystone factor aiding the flourish of DiY science is the rapid developments in what Fox (2014) refers to as 'Web-based Third Wave DIY' - the proliferation of collaborative and low barrier mediums like web communities, online videos, and entrepreneurial-oriented media like the Make Magazine and the Maker Faires (Tocchetti, 2012; Dougherty, 2012). These modern technologies are allowing makers to structure and engineer their ideas and creations while also lowering the learning curve through social network communities, video publishing sites and online forums (Kwon and Lee, 2017; Fox, 2014; Cressey, 2017). They also provide platforms through which used-and-inexpensive equipment – central to the operations of DiYers – can be sold and purchased (Meyer, 2012, 2013). Besides the low barrier mediums, the low entry barriers into DiY labs, unlike traditional academic institutions, are also aiding the spread of DiY, as expressed by Mohomed and Dutta (2015)

> The community of makers utilises traditional manufacturing techniques.... The special twist is that one does not need to go through an apprenticeship process and commit to years of study along with a vocation...Rather, one can simply find the closest hackerspace and join up... (p.41).

The rise of DiY practices and the Maker phenomenon has much to do with the current industrial economies, processes and advancement in batch fabrication technologies (Mota, 2011; Gershenfeld, 2012). With our current economy thriving on regular obsolescence associated with the acceleration of production, spawning a surplus of disposable high technology, the cost of hacking, making and experimentation has become greatly lowered (Mota, 2011; Delgado, 2013). Similarly the explosion in new materials and technologies such as 3D printing, laser-cutting and garage scale CNC mills for personal fabrications has allowed hobbyists and the hacking community to build the little things that enable a Makerspace to get up and running much faster than ever before (Baden et al., 2015; Tanenbaum et al., 2013; Mota, 2011; Cressey, 2017; Gershenfeld, 2012). The increased interest in the DiY culture can also be credited to the open feature of its devices i.e. they come accompanied by guidelines on how they were produced, giving users the opportunity to replicate, modify and develop them (Delgado and Callén, 2017;

Rognoli et al., 2015) without compromising function (Kim and Shin, 2016). With regards to synthetic biology, for example, and as intellectually prognosticated by Carlson (2001), see also (Dyson, 2007), the increasing productivity and precipitous decline of the cost curves for DNA sequencing and DNA synthesis (Ledford, 2010; Carlson, 2003) has been crucial in the advent of biological technologies "from academic labs and large biotechnology companies to small businesses and eventually to the home garage and the kitchen" (Carlson, 2001, p.16). Combined with free and open sharing of detailed design blueprints and accessible development tools, (Baden et al., 2015), DiYbio for example is speedily moving out of institutions to the realms of the public (Delgado, 2013). Elsewhere Meyer (2013) reveals that not only is DiY practices proliferating as a result of the availability of cheap equipment, it is also gaining ground as a response to the call for creative solutions to deal with the reality that scientific equipment is usually unaffordable and hard to come by, see for example (Yoshino, 2017; Damase et al., 2015).

Relevance of DiY science as an alternative science model

Healthcare

With the underlying assumption that physicians and health professionals are experts rather than the patients, most health care systems have long embraced a top-down model of health production, in which large scale organisations such as pharmaceutical companies or licensed health centres produce the equipment and technology for improving health (Lee et al., 2016). However through the production of low-cost and portable technologies, it is becoming apparent that the bottom-up, patient-driven medical devices associated with DiY healthcare is filling an important gap in the health care landscape (Dolgin, 2010; Carrera and Dalton, 2014; Raju et al., 2016). DiY practices through its open source mechanisms and production of low-cost materials is making an important technical contribution to health care delivery by empowering citizens with the knowledge and techniques needed to practically engage with medicine, allowing non-scientists to examine themselves, for example, for genetic diseases (Dolgin, 2010), gene therapy (Ireland, 2017) and tropical diseases like Malaria (Landrain et al., 2013). In an era of open science and the use of technologies to monitor patients in point-of-care settings within the Internet of Things (IoT), biohackers are employing self-experimenting technology in order to track their daily physical and biochemical activities to build a library of personal informatics in order to maintain a healthy lifestyle or improve body performance (Yetisen, 2018; Wexler, 2016; Duarte, 2014).

Here the famous case of the 'Nightscout Project' is worth mentioning. As presented by Lee et al. (2016) this project started when the parents of a young boy with newly diagnosed type 1 diabetes began using a continuous glucose monitoring system (CGMS) approved by the US Food and Drug Administration (FDA) that would provide interstitial glucose readings every 5 minutes. However although the information proved useful, the parents could not monitor the child's blood glucose level when he was in school. This is because there were no commercially available mobile technology solutions to access the data in real time. Thus the father, a programme engineer, started developing a computer code that would enable him to access the blood glucose readings from the CGMS receiver to the computing cloud through a smart phone. With the data in the cloud, the blood glucose level could be viewed by the parents from anywhere to provide a continuous monitoring solution.

When the father succeeded in transmitting his son's blood glucose data to the cloud, he adopted a do-it-yourself model of dissemination by openly sharing his achievement on social media platforms. Here other caregivers, patients and those with technical programming expertise contacted the father. The computer code was shared with these individuals, and as a group they began using, adapting, and creating new code to develop novel and personalised mobile technology solutions, including displays of glucose values that served as care portals to allow caregivers to input additional data (insulin doses, carbohydrates), smartphone applications with alerts for high or low levels of blood glucose, and real time views of blood glucose levels on wearable computing devices like programmable wristwatches. The group decided to make the computer code open source, including the smartphone application for transferring data from the CGMS to the cloud, the web application to display values stored by the CGMS and the watch face for a wearable device that displays the values open source. A website was then created that hosted the code and do-it-yourself written instructions and informational videos for setting up the system. Similar to the many online community groups that help in the proliferation DiY science, the group opened a Facebook group that became a community forum where members could learn more about the system and ask for and receive technological advice and troubleshooting. Important to the discussions in this study Lee et al. (2016) note that the Nightscout Project showcases the increasing autonomy, of patients, caregivers, (and DiYers) in the context of computing revolution, with smartphones and the internet empowering patients to design and create their own technology systems for health without the need for assistance from industry or health care professionals. Thus according to Meyer (2013) DiYbio is fostering a distinct form of individuality by providing people with access, transforming them into makers of science, making their bodies/ailments more knowable.

Educating the masses

DiY practices are not only making important contributions to the health care delivery system; they are also making significant contributions in the educational sector. The DiYbio community offers a range of affordable and easily accessible educational and entrepreneurial opportunities for the public; they reach out to the lay public and students with hands-on training and education that would otherwise be available only to university students and those in industry (Grushkin et al., 2013). DiY science is making invaluable contributions to the production of knowledge by reducing the cost of experiments through the production of inexpensive alternatives to premium laboratory products that previously required institutional or private funding (Seyfried et al., 2014; Bezuidenhout, 2018; Landrain et al., 2013). A typical example is the production of the low cost but effective KdUINO instrument used to measure water transparency (Bardaji et al., 2016). Such innovative products are transformative and in/directly aid research by not only making equipment more available to DiYers, but also opens the technology to educators and students in the traditional academic settings (Grushkin et al., 2013). Also DiY online curricula and peer communities offer constructive feedback on projects, technical support and expertise for enthusiasts seeking to produce or purchase low-cost materials for DiY and other projects (Kuznetsov and Paulos, 2010; Fox, 2014; Grushkin et al., 2013). These online communities include Instructable community hub (Instructables, 2019),where DiYers share the products they do as well as provide guidelines on how they do it for others to rate and comment; *Adafruit,* an online distributor of micro-electronics parts and kits, as well as a platform for general tutorials on the making of low cost materials; *Arduino*, an open-source electronic platform based on easy-to-use hardware and software, intended for anyone making interactive projects, see also (Kuznetsov and Paulos, 2010; Fox, 2014).

The pertinence of DiY science has been explored through research works that have aimed to highlight the cognitive, character-shaping and the intellectual-building potential associated with Making experiences in education, see (Agency by Design, 2015; Sheridan et al., 2014). These studies usually substantiate the learning through making argument by employing the 'theory of constructionism' (Papert and Harel, 1991). This theory posits that students are able to build knowledge and better understanding of concepts by constructing physical and digital artefacts in traditional learning settings as well as makerspaces. Many studies in this strand of literature celebrate Making as essential in the promotion of education in general and science education (science, technology, engineering and maths – STEM) in particular for young students (Bevan, 2017; Peppler and Bender, 2013; Martin, 2015; Schön et al., 2014). According to Chu et al. (2015) Making promotes a maker mindset; and stimulates learning (Sheridan et al., 2014). Equally importantly Making can potentially broaden participation and interest in science and STEM learning to include students from communities historically underrepresented in STEM fields (Bevan, 2017). Chu et al (2017) found that Making intervention in public schools fosters students sense of self efficacy in Making leading to positive outcomes such as students' self-identification as possible future scientists and engineers or other STEM-related persons also. Becker and Jacobsen (2019) present evidence from an Elementary school in Canada to show that makerspaces and Making can help young learners and teachers embody the ontology of a scientist. To Holbert (2016) Making fosters knowledge building. In this regard other findings have shown that 'Tinkering' provide opportunities for learners to practice relevant skills such as collaboration, problem solving, innovating and learning from failure (Bevan et al., 2015). Through the deployment of low and high tech materials to innovate solutions to problems, work undertaken in makerspaces builds discipline knowledge and develops cognitive capacities for creativity in a knowledge economy (Vossoughi and Bevan, 2014; Vandevelde et al., 2016).

Summarily the findings of the preceding literature on the effect of making on education indicate the individual-centred experiences students acquire as they tinker and hack things. However, findings elsewhere have shed more light on the sociological dimensions of maker-centred experiences students acquire in Making. These findings, gleaned from interviews with maker education practitioners and thought leaders working across a variety of contexts indicate that, equally importantly, the benefits of maker-centred learning for young people borders not only on the development of a sense of self, but also on the development of a sense of community that empower individuals to engage with and shape the designed dimension of their world (Agency by Design, 2015). Thus we note that Making has both psychological and sociological attributes. In both the short and long term it captures the holistic ideals of education i.e. by developing the technological skills of individual students as a way of increasing human capital (or human capacity to make the individual useful to themselves); and also by contributing to the externalities of education beyond the individual by instilling sociological skills for the broader good of society.

DiY vs. institutionalised science: An ambivalent relationship

Worth noting however is the fact that although DiY science and the Maker community have a reputation for democratisation of knowledge and an avowed filiation with open source principles, which in a way opposes some of the symbolic ideals of institutionalised science , the flourish and the growing importance of DiY practices is multiply dependent on an ambivalent relationship between DiY and institutionalised science (Keulartz and van den Belt, 2016; Penders, 2011; Ikemoto, 2017). DiY science thrives on institutionalised science, depends on it (Kelty, 2010) and operates in its backyard (Ikemoto, 2017). Concerning the production and use of scientific materials, DiY thrives on institutionalised science in that many of the open source tools that are available on the internet have been produced in institutionalised settings (Delgado, 2013; Kelty, 2010). As already noted the availability of garage-cheap equipment is central to the existence of DiY. However most of the used-and-out-of-date materials, available to DiYers at low cost, are as a result of technological accelerations within institutionalised science business (Keulartz and van den Belt, 2016). With regards to human capital, most of the leading figures and practitioners of the DiY community who provide the collective expertise have received formal education from universities and other leading educational institutions. Grushkin et al (2013) reveal in their survey of the DiY community that 19% had obtained doctorate-level degree, 27% had a master's degree, and 37% had completed college. Thus the knowledge and expertise they bring to bear on DiY communities have been shaped by academic institutions. Another example will highlight this point – Josiah Zayner, a leading figure in the biohacking community is a former Nasa biochemist, see (Ireland, 2017). With regards to the DiY brain stimulation community, for example, Wexler (2016) shows that in the processes leading to the stimulation of their own brains with transcranial direct current stimulation (tDCS), DiYers rely heavily on existing scientific knowledge, posting links to academic journal articles and scientific resources and adopting the standardised electrode placement system used by scientists. In addition some DiYers co-opt scientific knowledge and modify it by creating their own manuals and guides based on published scientific literature. This calls for some cooperation between DiYers and institutionalised science but care must be taken that DiY does not lose its most treasured ideals of democratisation of science and open source principles.

DiY science and the promise of innovation

DiY science, as the site for the identification for opportunities for innovation, has come to represent open innovation crucibles where new ideas emerges, develop, and grow over time (Gonelli and Ruivenkamp, 2016; Nicholson, 2012; Wolinsky, 2009). Following Von Hippel (2005), we note that most DiY practices, which are becoming commonplace due to design capabilities (innovation toolkits) and the open sharing of innovation-related products, fit the user-centred innovation model. But how does this model specifically birth innovation? Von Hippel (2005) explains that as opposed to manufacturer-centred innovation where innovations are patented with economic and commercial intentions, the advantage in the user-centred innovation is that the shared design or product (without patent – the ethos of the DiY communities) can be modified or better upgraded by other innovators in the user community. Thus a chain of innovative-product enhancement activities is formed by users (who are usually the forerunners in the development of most new industrial and consumer products). In this sense the propensity of DiYers (users) to freely reveal what they have developed; to employ toolkits to tinker, make and prototype objects in order to suit specific needs is promissory of the creation of novel products, see (Von Hippel and Katz, 2002; Von Hippel, 2017). The Nightscout Project described in section 3 typifies this user-designed, technology driven collaborative product innovation (Von Hippel, 2017). Meredith Patterson's glow-in-the-dark yoghurt made by engineering the bacteria within to produce a fluorescent protein (Nature, 2010) also speaks to the innovative potential of DiY practices.

Other authors have emphasised the innovatory promise of DiY based on the principle that the best way to have a good idea is to brainstorm on a lot of ideas. In their view the rising promise of DiY science to innovative research is becoming more apparent because the other two traditional drivers of innovation namely academic institutions and industry are becoming 'innovation-unfriendly' (de Lorenzo and Schmidt, 2017; Sarpong and Rawal, 2020)). Funding agencies and journals also seem to discriminate against ideas that are not in conformity with the mainstream leading to the preferential funding of predictable and safe research over radically new ideas (Nicholson, 2012). According de Lorenzo and Schmidt (2017), the strict policy by academic institutions to focus on specific topics and their publication in high impact factor journals sometimes set students up on the path of failure of innovative research. They express:

> ...when young scientists face a thematic choice, the panic to failure and ridicule at an early stage of one's academic career often place invisible barriers to creativity and curb the pursuit of new ways to tackle scientific and technological questions (de Lorenzo and Schmidt, 2017, p.517).

In industry the expressive fear about Intellectual Property (IP) not only stifles frank discussions among specialists on a given topic (one of the best cradles for new ideas) but it also kicks very inventive minds away from the industrial space (de Lorenzo and Schmidt, 2017; Von Hippel, 2005). DiY thus has become the way out for free-minded innovation (Lindtner et al., 2014; Lindtner, 2014). These innovation processes are pillared in the "making is better than buying" ethos (Tanenbaum et al., 2013) and is exemplified by what Meyer (2012, 2013) terms the 'creative workarounds' which biohackers have developed to replace standard laboratory equipment which are too expensive for personal use.

According to Landrain et al. (2013) the huge promise of DiY activities to biological innovation, for example, can be found in the annual International Genetically Engineered Machine (iGEM) competition which brings together undergraduate students from across a range of disciplines to work collaboratively to build biological systems of their own design using interchangeable biological parts and standard molecular biology techniques. The competition which is linked to the parts-based approach to synthetic biology through its contribution to the Registry of Standard Biological Parts (Frow and Calvert, 2013) has recently witnessed ambitious projects such as the 'Oh My Gut' project. This project developed by students from Taiwan has engineered a synthetic biological approach to tackle kidney related diseases (iGEM, 2019). The takeaway point is that by providing unmediated access to spaces and open source technology, DiY community labs and their practices are providing fertile grounds for individuals to combine and coordinate their innovative-related efforts. The production of DiY materials, their design, their assembly etc are shaped and reshaped through iterations of presenting prototypes on websites, receiving online feedback, presenting modified prototypes, receiving further online feedback, and so on (Rognoli et al., 2015; Fox, 2014). Through this, barriers to innovation are minimised as individuals can easily access external resources as and when they require them. Further, restrictions on innovation are reduced through the networking of DiY groups. Hence knowledge of innovation practice can be extensively evolved and widely distributed (Fox, 2014). By extension the creative freedom which allows individuals to make whatever complicated products they imagine can engender the development of novel products in the field of medicine (through DiYbio) and technology (through the maker related activities). This is truer considering that the growth of maker-related activities prominently underpins the success stories of many Silicon Valley start-ups as remarked by Josiah Zayner:

> I grew up in the 90s with the computer hacker movement, the development of the internet – the whole open source movement was amazing. Who created Linux, the most used operating system ever? Not students from Harvard or Cambridge but Linus Torvalds, a student in Finland working in his apartment (Ireland, 2017).

Potential concerns about DiY science

Bioterrorism, biosafety and biosecurity

Sensational and alarmist headlines about DiY science argue that the practice could serve as a context to inducing rogue science that could potentially lead to a zombie apocalypse. In the extant literature, concerns regarding the operational risks of DiY science are mostly related to synthetic biology, biosafety and biosecurity see (Schmidt et al., 2009; Bügl et al., 2007; Dana et al., 2012) and DiY medicine (Akst, 2013). Synthetic biology (Synbio) as highlighted by Ahteensuu (2017) concerns the combination of molecular biology, genetics, chemistry, physics, computation/information technology (IT) and engineering. The definition dynamics of Synbio usually involve two aspects. Firstly, it is about redesigning natural living systems to fulfil specific purposes, for example, to produce drugs (eg artemisinic acid) or biofuel. Microbes are modified and to some extent constructed to work as living chemical factories. Secondly, Synbio involves constructing new kinds of living and (xenobiological systems) and their parts (Ahteensuu, 2017). Developments in synthetic biology, which are aligned with the generation of harmful organisms that can be deadly to humans and the natural environment, are considered to be closely associated with the growth of the DiYbio community, and concerns are raised that this could offer knowledge, tools and equipment to bioterrorists seeking to do harm (Jefferson et al., 2014). Thus on the basis of the realisation that past breakthroughs in the life sciences have regularly been misused for weapons purposes, Kelle (2009) argues that the security implications of synthetic biology must occupy the forefront of biological engineering discussions. This is related, in particular, to "myths" about increase in the "dual use" threat i.e. the potential for synthetic biology to be "used" for useful purposes or "misused" for warfare or terrorism (Jefferson et al., 2014).

We deem it necessary, here, though, to present how scholars characterise the terms 'biosafety' and 'biosecurity'. According to Ahteensuu (2017) and Ahteensuu and Blockus (2016) biosafety and biosecurity both generally refer to principles, practices and specific actions to prevent the use of synthetic biology for malicious purposes, coupled with possible unintended and unexpected consequences; they are mainly concerned with safety issues in the laboratory and, going forward, the deliberate release of synthetic organisms into the environment. According to the authors, while biosafety basically and for most part relates to the research personnel, the object of biosecurity – and in severe accidents also biosafety – is the general public in the vicinity of the company and the research sites, and the environment. They note that risks pertaining to the deliberate release may follow, for example, from the interaction, of synthetic organisms with the natural environment, and in the case of reproductive organisms, from evolution (Ahteensuu, 2017). To Kelle (2009) biosafety deals with the inherent risk of a biological agent or material to its environment, whereas biosecurity is concerned with the misuse of biological agent or material through, for example, loss, theft, diversion, intentional release of inadvertent research results. To Kelle (2009) pursuing biosafety goals and biosecurity goals are mostly complementary activities with a large area of overlap. However, in certain instances, approaches to achieve biosafety and biosecurity might be at odds with each other with one such example being the idea of engineering biosafety mechanisms into synthetic organisms to make them depend on nutrients that are unavailable in nature. Yet the principal problem with such a safety system is that someone with malicious intent could possibly short-circuit the fail-safe mechanism (Kelle, 2009).

Some analysts argue that bioterrorists might capitalise on the democratisation of information (mostly online access to the genomic DNA sequences of pathogenic organisms), and the ease of access to tools for biohacking (through the rapid proliferation of DiY science communities and the iGEM competition), to create synthetic pathogens to harm humans, see (Ahteensuu and Blockus, 2016). These concerns are countered by Jefferson et al (2014) that the generation of synthetic pathogens require socio-technical resources that are not generally available to DiYers. The expensive nature of the infrastructure required serves as an obstacle to such enterprise (Jefferson et al., 2014). Moreover the link between bioterrorism and DiYbio, and the level of sophistication of the experiments typically being performed in DiYbio community labs is overstated (Grushkin et al., 2013). As argued by Golinelli and Ruivenkamp (2016) the main aim of DiY practitioners is not to develop a 'new miracle' product but to reconnect existing products to practical social needs. In addition, members of DiYbio communities who are involved in more sophisticated experiments tend to be trained biologists, not amateurs, who are more proactive in addressing and engaging with safety and security concerns in many community laboratories (Grushkin et al., 2013; Kuiken, 2016). Also most DiY communities in the US, for example, collaborate with the FBI on security issues (Tocchetti and Aguiton, 2015).

Beyond the possible safety risks, drawing on the historical activities of computer hacking where people with malicious intents create software viruses for nefarious purposes, Mukunda et al. (2009), warn that the de-skilling of synthetic biology would make the technology readily available to individuals and groups who would use it to intentionally cause harm. However, some analysts note the high improbability of this scenario given that the effective use of synthetic biology techniques relies on skills and techniques that cannot be easily codified (in this case not easily found on the internet), but, rather, are acquired through a hugely lengthy process of 'learning by doing' or 'learning by example'. This is what these analysts refer to as 'tacit knowledge' (Revill and Jefferson, 2013; Jefferson et al., 2014). Here we draw on the discussions as presented by Tucker (2011) and Jefferson et al. (2014) in order to reveal the dynamics of the biosecurity risk assessment. In the assessment of risk of misuse, it becomes pertinent to differentiate among potential actors according to their financial assets and technical capabilities – from states with well-developed bio-warfare programmes to terrorists' organisations of varying size and sophistication to individual hackers with motivated by ideological or other grievances. As revealed by the study of state-level bio-warfare programmes, the production of biological weapons necessitates an interdisciplinary team of experts with expansive knowledge in fields such as microbiology, aerobiology etc. States are therefore generally more capable of organising and sustaining such teams than non-state actors. But what if some powerful terrorist groups, aiming to produce the biological weapons, manage to acquire the needed human and capital resources? Here Ouagrham-Gormley and Vogel (2010) reveal social-context barriers that can thwart the efforts of these groups. They note that even in the unlikely event that terrorist could recruit such science experts, its members would still face the challenge of adapting the technology to a local context. In addition, dysfunctional group dynamics such as refusal by some team members to cooperate would also create problems to interdisciplinary team work in areas requiring communal tacit knowledge.

But what if the terrorist groups are able to overcome these social obstacles? Here Jefferson et al demonstrate among other things that there are huge obstacles that face the production of biological weapons. They submit that constructing a genome size DNA fragment is not the same as creating a functional genome. In particular ensuring the desired expression of viral proteins is a complex challenge. Since there are huge challenges to the processes of scaling up, storage and developing suitable dissemination methods, producing viral particles in a laboratory does not equate the creation and deployment of an effective biological weapon. In effect Jefferson et al (2014) summarily demonstrate that any bioterrorism attack will mostly likely be one using a pathogen strain with less than optimal characteristics disseminated through crude delivery methods under imperfect conditions and the potential casualties of such an attack are likely to be much lower than the mass casualty scenarios frequently portrayed. In effect the Synbio risks associated with the DiY practices are not in the sphere of current possibilities.

Implication for policy

Arising from the literature, one can observe that the DiY movement is gaining energy and momentum. It can also be observed that the practice has the potential to make significant contributions to various sectors such as health, education, and product innovation. Although safety risks exist, they are currently at very low levels, and can still further be minimised through increased vigilance. Thus, from the perspective of our survey we make recommendations which can have relevance either for the continuous survival of DiY practice and for the preservation of its integrity, or as way of way of harnessing maximum benefits from the movement. Our recommendations mostly concern the extension of assistance to DiY community labs so as to increase their operational capacity. However, we particularly note that in seeking to collaborate with BigBio and governmental institutions, the DiY communities must ensure that they are not co-opted in ways that may undermine their novel ideals of democratisation of knowledge and open sharing. Our recommendations correspond with the aspects of the DiY practice examined in the study and are described briefly as follows:

The flourish: We find that most of the community labs are established in the Global north (http://diybio.org/local/). Meanwhile most science departments in universities in developing countries, especially in Africa, lack the necessary equipment to conduct practical experiments (Bezuidenhout, 2018). Obviously, funding is the biggest challenge. The establishment of community DiY laboratories, with its emphasis on the production of innovative but low cost equipment would therefore help bridge this gap, see for example (Bezuidenhout, 2018). Educational authorities and school instructors in developing countries should therefore find more innovative ways to incorporate the DiY culture into the school curriculum. Also, International development organisations seeking to promote STEM education in developing countries should begin to look at the setting up of DiY community labs. Providing opportunities for students and practitioners to build their own teaching/learning equipment using locally-sourced materials would minimise the dependency on expensive, foreign-manufactured equipment which is a major obstacle for the advancement in practical science experimentations.

The relevance: Considering the importance of DiY to science education, we recommend that institutionalised science can formally have joint educational partnerships with DiY communities. As already explained DiY thrives on garage-cheap equipment. In this case tertiary institutions and BigBio can offload most of their old equipment to DiY labs cost-free. This will obviously increase the capacity of the community laboratories. In return institutionalised science can use the DiY labs as experimental zones for amateurs to try out ideas and gain experience prior to entry into the mainstream science in the tertiary sector.

Also, most studies that have looked into the matter concerning Making and its influence on education concur that children become inclined to science when they make. However other studies have found that while many girls may express a more active engagement in science during their early school years, they increasingly find science classes and science-based careers less appealing as they progress through high school (Chu et al., 2017; Murphy, 1994). We therefore recommend that to promote long term interest in STEM fields for girls, making activities be seriously incorporated into the educational curricula from the early stages to the high school level. Equally importantly community laboratories should target education and STEM skills training towards young girls as this is likely to have a relatively large impact on their interest in science related fields.

Innovation: In relation to industrial innovation, Von Hippel (2017) reveals that the development of valuable products by consumers, coupled with the 'free innovation' processes represent a resource for producers. Thus, instead of replicating the innovative processes already done by consumers (free innovators), industrial innovators often collect and assess these designs to identify those with the highest economic potential and apply their finances to refining these designs. Thus, not surprisingly many companies are beginning to collaborate with free innovators by providing support to individual innovators. We however recommend that manufacturing firms must begin to collaborate with and support DiY community laboratories (who are also valuable agents of free innovation). The support can come in the form of provision of infrastructure facilities and equipment. Also, government policy should provide increased financial and technical support to the DiY communities. This can come in the form of tax incentives and subsidies.

Concerns: The study finds that most of the security concerns raised by the public security institutions and some science experts are not grounded in an explicit understanding of the underlying principles of the DiY community labs and garage laboratories. The fears related to the production of bioweapons by DiYers are currently unfounded. However, although the DiY labs are registered and are therefore subject to monitoring procedures, most of the concerns relate to the individual experiments undertaken in private homes and garages. Here the DiY labs should intensify flexible registration procedures and initiate steps to reach out to these enthusiasts and encourage them to register.

Conclusion

This paper set out to survey studies on DiY science practices, and distil factors that fuel the proliferation, the relevance, as well as the risk-framing discussions engulfing the DiY phenomenon. Our aim was premised on the fact that DiY practices continue to pick up both momentum and stigma. The practice has often alternatively been hyped and decried as the panacea to the ills of society or the nursery for a bioterrorist scourge (Ledford, 2010). Thus, we set out to profile the current literature on the DiY landscape in order to provide a knowledge repertoire and thus guidance for practitioners, non-practitioners and policy which can potentially minimise the myth and the hype as well as improve the quality and effectiveness of policy measures aimed at the DiY science practice. Overall, we see that the proliferation of the internet and web-based communities serve as a major contributing factor to the proliferation of this novel practice. As observed by various commentators, DiY is gaining increasing momentum because most science enthusiasts are clinging to the practice as a way of escaping the stifling nature of institutionalised science with its over-mediated production of knowledge. In addition, the availability of garage-cheap equipment fuels the thriving of the DiY practice.

It is noticeable that the DiY production of low-cost and portable technologies is making important contributions in the health and educational sectors. Besides, the DiY community is offering alternative platforms for affordable and easily accessible educational opportunities. Equally importantly the open source and open sharing principles of the DiY practice is providing unlimited opportunities for the promise of the birthing of innovative products. By providing unrestricted access to learning spaces and open source technology DiY practices are fostering the combination and coordination of innovative related efforts.

While emphasising the relevance of DiY science one must also acknowledge that the practice is not without risks, although not on the scale often portrayed especially by the media. Although some studies have shown that biohacking performed in unregulated settings can potentially result in negative medical conditions including body pain and trauma (Yetisen, 2018; Giger and Gaspar, 2019; Wurzman et al., 2016), the grand bioterrorism framing connecting DiY practices and synthetic biology, biosafety and biosecurity have been shown to be far-fetched. In the worst case scenario, studies have demonstrated that any DiY-bioterrorism attack would most probably be employing a synthetic pathogen strain with minimum characteristics disseminated through crude delivery methods under imperfect conditions and the potential harm of such an attack are likely to be much lower than the mass casualty scenarios frequently portrayed (Jefferson et al., 2014). Some years after this imperious empirical analysis, we find no study, at the time of writing our study, that has provided evidence to the contrary. We therefore note and agree with other analysts that the serious bioterrorism attack often associated with DiY practices is unrealistic in the current circumstances.

Although DiY-bioterrorism attack is not in the realm of current possibilities, we however acknowledge that technology is improving fast. Therefore, the tacit knowledge and expensive equipment required to engineer harmful synthetic organisms can be acquired over the long time by DiY malefactors. There are, therefore, good reasons to monitor the operations of the DiY community members. In this regard the bottom-up 'neighbourhood watch' stance adopted by the FBI where biohackers monitor their own community and report behaviour they find threatening (Ledford, 2010; Tocchetti and Aguiton, 2015) is a useful approach. A high-handed regulation approach to monitor DiY community laboratories, due to fear of bioterrorism, would only stifle the innovative potential of DiYers. As expressed by MacKenzie Cowell, a co-founder of DiYbio, in any case, with or without the DiY community members, terrorists are going to find ways and means to gain the knowledge, equipment and skills that they require to conduct their illegal activities (Wolinsky, 2009). "Enabling more people to do biology isn't necessarily going to be the bottleneck. By stopping amateurs, that doesn't really stop terrorists" – MacKenzie Cowell cited in (Wolinsky, 2009). We therefore reiterate that considering the growing relevance of the DiY community laboratories and their practices to the expansion of the scientific frontier more technical and financial support should be accorded them as way of building their operational capacity. We follow Berditchevskaia (2017) to submit that increasing the accessibility and opportunities for members of the public to engage more deeply with the scientific endeavour through citizen science and DiY practices can reconfigure and foster a more equal debate on issues where the latest research has a significant contribution to make in terms of the challenges facing our societies globally such as climate change.

In order to further enhance the integrity and sustainability of DiY community laboratories and their practices this study recommends that future research should focus on the quality and long-term durability of DiY-manufactured equipment. As earlier stated, the continuous survival DiY practices depends on the availability of low-cost equipment. Thus, finding out the sustainability of these equipment vis-a-vis those manufactured by institutional science would shed more light on the long-term innovative prospects of the DiY phenomenon, and how policy measures could be structured to help DiYers improve the quality of their equipment or otherwise. Another relevant area of future research concerns a qualitative and quantitative analysis of DiY medicine and its (inter)relationship with what is usually considered as self-medication. Finally, further work is required that tests and assesses the quality of the educational training currently been offered by the DiY community laboratories.

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Appendix: Seminal papers on DiY science

Works	Area of interest	Publication
Baden et al. (2015)	Maker movement and technological equipment	PLoS biology
Bevan et al. (2015)	Making/Tinkering and STEM education	Science Education
Bevan (2017)	Making and science education	Studies in Science Education
Chu et al. (2015)	Making and child education	International Journal of Child-Computer Interaction
De Roeck et al. (2012)	DiY and internet-of-things product design	Proceedings of the 7th Nordic Conference on Human-Computer Interaction
Delgado (2013)	DiYbio and its relation with institutionalized science	Futures
Dougherty (2012)	Maker movement and its relevance to education and business	Innovations
Fox (2014)	DiY and information technology, innovation and entrepreneurship	Technology in Society
Gershenfeld (2012)	Making and digital fabrication	Foreign Affairs
Kelty (2010)	DiY science, hacking and their conceptualization	Journal of Science Communication
Kera (2012)	DiY, hackerspaces and knowledge production	Journal of Peer Production
Kuznetsov and Paulos (2010)	DiY projects and relations with Human-Computer Interaction	Proceedings of the 6th Nordic Conference on Human-Computer Interaction
Landrain et al. (2013)	DiYbio and technology development	Systems and Synthetic Biology
Ledford (2010)	DiYbio (Garage biology) and the relevance	Nature
Lee et al. (2016)	DiY medicine and the relevance	JAMA
Lindtner et al. (2014)	DiY products, Innovation and Human-Computer Interaction	Proceedings of the SIGCHI Conference on Human Factors in Computer Systems
Lindtner (2014)	DiY products and innovation	China Information
Martin (2015)	Making and education	Journal of Pre-College Engineering Education

		Research
Meyer (2013)	DiYbio and innovation	Journal of Material Culture
Mota (2011)	DiY and fabrication	Proceedings of the 8th ACM Conference on Creativity and Cognition
Peppler and Bender (2013)	Making and education	Phi Delta Kappan
Rognoli et al. (2015)	DiY materials and innovation	Materials and Design
Schmidt (2008)	DiY and biosafety	Systems and Synthetic Biology
Schön et al. (2014)	Making and education	eLearning Papers
Seyfried et al. (2014)	DiYbio and regulations	Bioessays
Sheridan et al. (2014)	Making and education	Harvard Educational Review
Tanenbaum et al. (2013)	DiY products, innovation and Human-Computer Interaction	Proceedings of the SIGCHI Conference on Human Factors in Computing Systems
Tocchetti (2012)	DiYbio and information technology	Journal of Peer Production
Vossoughi and Bevan (2014)	Making/Tinkering and education	National Research Council Committee on Out of School Time (STEM)
Watson and Shove (2008)	DiY product and designs	Journal of Consumer Culture
Wexler (2016)	DiY brain stimulation and biohacking	Journal of Medical Ethics
Wurzman et al. (2016)	DiY brain stimulation and biohacking	Annals of Neurology