D4.6 ETHICAL ISSUES IN EDUCATION AND RESEARCH

Project Acronym:	DiDIY
Project Name	Digital Do It Yourself
Grant Agreement no.	644344
Start date of the project	01/01/2015
End date of the project	30/06/2017
Work Package producing the document	WP4 – Analysing how DiDIY is reshaping education and research
WP Lead Partner	ABACUS
Other Partner(s) involved	all
Deliverable identifier	D4.6
Deliverable lead beneficiary	AC
Due date	M24 (December 2016)
Date of delivery	27/12/2016
Version	1.0
Author(s)	AC
License	Creative Commons Attribution ShareAlike 4.0
Classification	PUBLIC
Document Status	APPROVED
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 644344.	
Disclaimer: The views expressed in this document do not necessarily reflect the views of the EC.	

Disclaimer

This document is provided “As Is”; it is a study introducing the main research topics in the presented context. Any feedback, suggestions and contributions to make this document better and more useful are very welcome. Please let us know through the contact page http://www.didiy.eu/contact. We will seek to incorporate relevant contributions in the document and add your name to the list of contributors.

Executive summary

Deliverable D4.6, “Ethical issues in education and research”, undertakes to identify and analyse some of the main ethical issues pertaining to DiDIY in education and research, with a view to suggesting how to move forward (e.g., policy-wise) in the direction of progress. We begin, in section 2, by reiterating some clarifications about the concept of DiDIY, and specifying which view of it we will be relying on in our ethical analysis. Section 3 is devoted to the topic of DiDIY in education. Using D4.1, “Research Space and Agents”, as our initial starting point, we review the benefits and potential pitfalls of the introduction of DiDIY in the educational context, and consider additional relevant issues including the use of DiDIY to attract more women to STEM fields, and the need to educate young people on how to use DiDIY ethically. In section 4 we move on to discussing DiDIY in research. While highlighting its benefits, we do not find it to raise a wide range of unique ethical concerns (as opposed to concerns that it might inherit from other phenomena, such as citizen science). Because of this, we broaden the scope of our discussion in section 5 to cover DiDIY applications of cutting-edge research (including 3D bioprinting), both for therapeutic purposes and for human enhancement.

Revision history			
Version	**Date**	**Created / modified by**	**Comments**
0.0	4/3/2016	AC	First, incomplete draft.
0.1	30/11/2016	AC	Second draft, close to completion, sent to ABACUS for preliminary comments.
0.2	20/12/2016	AC, ABACUS	First full draft, submitted to all partners for comments.
0.3	26/12/2016	AC, ABACUS, LIUC	Revised draft.
1.0	27/12/2016	LIUC	Approved version, submitted to the EC Participant Portal.

Table of Contents

1. Introduction

As described in the other deliverables for WP4, the introduction of DiDIY in the educational and research contexts is already having a transformative effect. The present deliverable undertakes to identify and analyse some of the main ethical issues pertaining to DiDIY in education and research, with a view to suggesting how to move forward (e.g., policy-wise) in the direction of progress. We begin by reiterating, in section 2, some clarifications about the concept of DiDIY, and specifying which view of it we will be relying on in our ethical analysis. Section 3 is devoted to the topic of DiDIY in education. Using D4.1, "Research Space and Agents", as our initial starting point, we review the benefits and potential pitfalls of the introduction of DiDIY in educational contexts, and consider additional relevant issues including the use of DiDIY to attract more women to STEM fields, and the need to educate young people on how to use DiDIY ethically. In section 4 we move on to discussing DiDIY in research. While highlighting its benefits, we do not find it to raise a wide range of unique ethical concerns (as opposed to concerns that it might inherit from other phenomena, such as citizen science). Because of this, we broaden the scope of our discussion in section 5 to cover DiDIY applications of cutting-edge research, including 3D bioprinting, both for therapeutic purposes and for human enhancement.

Before proceeding, let us mention that for the "DiDIY in education" section of this deliverable, we will chiefly be focusing on the context of compulsory education, mostly up to the level of secondary school, rather than on higher (college-level) education. The reason for this is that the former context is where most of the examples of DiDIY in education are to be found so far, and it is also chiefly in this context that some are advocating significant reforms revolving around a "maker-based" model of education and the principle of "learning by making". We will, however, have a few words to say about DiDIY in higher education as well.

2. Some basic conceptual clarifications

2.1 Technical terms and acronyms

Term	**Meaning**
ABC	Atoms-Bits Convergence
CAD	Computer-Aided Design
CNC	Computer Numerical Control
DIY	Do-It-Yourself
DIYer	individual or organisation (formal or informal) that engages in DIY
DiDIY	Digital Do-It-Yourself
DiDIYer	DIYer that engage in DiDIY
DiDIY design	(1) process of designing an object by a DiDIYer, usually by means of CAD software (2) digital blueprint resulting from a process of designing an object by a DiDIYer
DiDIY manufacturing	manufacturing of a DiDIY product
DiDIY product	product created by a DiDIYer using one or more DiDIY tools
DiDIY tool	DiDIY resource as physical or virtual tool or machine directly used in physical or design work for the purpose of engaging in DiDIY
Fab Lab	makerspace structured according to a specific model of DIY, as proposed by the MIT's Center for Bits and Atoms
GA	Grant Agreement
IoT	Internet of Things
IPR	Intellectual Property Right
KF	Knowledge Framework
makerspace	community-operated physical place that affords sharing of tools, resources and knowledge motivated by maker culture, revealing specific ways of creation, collaboration and learning
MOOC	Massive Online Open Course
prosumer	a person who combines the roles of producer and consumer with regard to one and the same product
STEM	Science, Technology, Engineering, and Mathematics
SV	Shared Vocabulary

2.2 How to understand DiDIY: reminders from the Knowledge Framework

Our understanding of DiDIY in this deliverable is reflected in the preliminary remarks we made in subsection 2.2 of deliverable D3.3. We will also rely on the explanation of the concept presented in three foundational documents: the Grant Agreement (GA) for this Project, the DiDIY-related shared vocabulary (SV), and the revised version of the Knowledge Framework (KF; deliverable D2.4).

In this document our focus will mostly be on the objective facet of DiDIY, even though we will also take the subjective component into account. Understood as an activity, DiDIY involves, among other things, the use of technologies like 3D printing, CNC milling, laser cutters, and other digital manufacturing devices, by hobbyists rather than professionals, as illustrated by the rise of the contemporary "maker" movement. DiDIY goes beyond this to also incorporate, e.g., the modification of existing objects (which could be made "smart" with the help of devices such as Arduino boards). On an even broader understanding of the concept, DiDIY could even go beyond the realm of physical objects and include all uses of digital technology in a DIY manner, e.g., the writing of articles on a personal blog or the design of web content for non-professional purposes. In this complex context, we will mainly devote our attention to the narrower understanding of DiDIY that includes ABC, following in this deliverable D4.1. We will, however, occasionally have some remarks to make about DiDIY in the broader sense as well, as illustrated for instance by the references to Massive Online Open Courses (MOOCs).

3. DiDIY in education

3.1 Existing and proposed applications

As explained in D4.1, "Research Space and agents", DiDIY has already started entering the world of education in various ways. Fab Labs or similar workshops are being opened in a growing number of schools, where they bring the latest digitally-driven equipment to be used for design and engineering classes – contexts in which the relevance of such equipment is clear enough. 3D printers have also been put to use for science classes such as physics and mathematics. Non-profit organizations in Africa such as Youth for Technology are promoting 3D printing as a means of getting more women to study STEM subjects (*ibid.*, p. 13). In the context of mathematics, 3D printing can be used as an aid to visualize mathematical objects. Similarly, in the field of geology, the technology can help students understand geological formations.[1] D4.1 also mentions that DiDIY electronics such as Arduino or Raspberry Pi are naturally suited to the educational strategy of the "flipped classroom" – which turns the classroom lecture into homework, for example in the form of video lectures that students watch at home, and allows teachers to devote class time to working on the solution of problems with students. The document also considers extra-curricular activities, including educational initiatives like the RoboCup Junior and the First Lego League, both involving competitions that aim to get elementary and middle school students involved in robotics (pp. 16-20).

Some argue that DiDIY tools – especially 3D printing – also hold great potential for other fields where they are yet to be widely adopted. Such domains include history and art. History teachers who cannot bring their students to a particular museum might thus still be able to bring the museum to their students by downloading and printing digital replicas of ancient artefacts, in cases where museums make the relevant digital blueprints available online. This is for instance the case of the British Museum, which has created a "SketchFab" webpage featuring a number of its artefacts that have been 3D scanned and made available there in the form of digital files that its online visitors can visualise and print.

3D printing has been cited as opening "a whole new realm of possibilities for art teachers" (Krassenstein 2014), who could include 3D design into their lessons and thereby provide their students with tools that would enable them to create things they would never have been able to create otherwise. Furthermore, the technology would also facilitate collaborations between different classes, potentially located in different countries, which could work on common projects together and then 3D print the results in each of their respective locations (*ibid.*).

Beyond the simple introduction of DiDIY into the classroom in order to "augment" the teaching of some subjects, however, some key figures in the "Maker" movement are advocating its use, among other measures, in order to effect a complete overhaul of the current educational system. For instance, Dale Dougherty, the founder of *MAKE* magazine and the creator of Maker Faire, has accused contemporary schools of failing to engage students and of expecting them to passively absorb content insufficiently connected to the real world. As an alternative, Dougherty proposes to use DiDIY to help students become "active participants in constructing a new kind of education for

1 Going back to the Knowledge Framework, let us add that uses of 3D printing in such contexts will only count as DiDIY provided that the artefacts that are thereby produced are either designed or manufactured by people who are not acting as professionals. As an example, a teacher who purchased ready-made 3D printed mathematical figures for his class from a commercial online service would thus not be engaging in DiDIY.

the 21st-Century", which would promote creativity and critical thinking and would be based upon the principle of "learning by making", inspired in part by the ideas of philosopher John Dewey. To the objection that such an approach to education might not allow to measure the extent to which students have gained true learning from it, Dougherty (2012) retorts that:

> "Making creates evidence of learning." The thing you make – whether it be a robot, rocket, or blinking LED – is evidence that you did something, and there is also an entire process behind making that can be talked about and shared with others. How did you make it? Why? Where did you get the parts? Making is not just about explaining the technical process; it's also about the communication about what you've done.

A number of other authors have defended claims similar to Dougherty's (see, e.g., Krassenstein 2014, and Martinez, Stager 2015).

So far, all the forms of DiDIY that we have been discussing have involved the building of physical artefacts using digitally-driven manufacturing devices. However, there is also a contemporary educational tool that could be considered DiDIY in a broad sense, and does not involve any such manufacturing process: namely MOOCs, i.e., courses available in open access via the web. They rose in popularity at the start of the present decade, and have often been touted as having the potential to truly revolutionize education. The rationale for describing them as a form of DiDIY would be that they are based on a digital platform, and that they put students in charge of their own learning, since they can take a course out of their own initiative, go at their own pace, and test themselves at the end, on account of which one might attach the label "DIY" to this form of education.

Let us note, however, that MOOCs may be most relevant to *higher*, i.e., college-level, education. Indeed, most MOOCs made available online come from University instructors. It has been argued that "professors from elite colleges typically know little about pedagogy, even as they have expertise in their particular subject matter", and that "as a result, the pedagogy behind most MOOCs is weak, and the MOOCs are not well suited for high school students" (Horn 2014). Furthermore, it is more difficult to let students at the high school level and below take charge of their own education – though that is not to say that MOOCs have nothing to offer such students. The teachers interviewed for D4.4, for example, agree that this kind of self-education might be well suited for so-called "strong students", i.e., those with sufficient autonomy and self-discipline to lead their own education (who might also be found in some high schools), even though it would be disastrous for those who would rather benefit of a more structured approach. On a related note, Horn mentions MOOCs' potential usefulness for gifted students (Horn 2014).

3.2 The promise of DiDIY in education

The introduction and promotion of DiDIY in education promises to bring a number of benefits. Most of these are already detailed in D4.1, so we will content ourselves with briefly recapitulating the main ones here.

- First, giving students the opportunity to work on their own projects using the latest DiDIY tools helps them develop early on various skills that can be of great value to them later in life: not just design and engineering skills, but also problem-solving and collaborative skills and a sense of initiative more generally.

- Secondly, exposure to DiDIY might help add an exciting element, as well as a more hands-on feel, to the teaching of STEM subjects, which can sometimes seem arid, intimidating, or overly abstract. In this respect, those who promote the introduction of DiDIY in schools can point to surveys indicating that American teenagers are dissatisfied with the emphasis on textbook-centered teaching that they usually get in their science classes, and would like to experience more hands-on science at school. Also, DiDIY has more specifically been described as a potential tool to attract more members from under-represented groups, such as women, to the study of STEM subjects – a crucial issue in a context where, as we have described in deliverable D3.3, "Ethical Issues and Work", an increasing number of future jobs are expected to require advanced STEM literacy (we will address the issue of women and STEM subjects in more detail in subsection 3.4).
- Thirdly, DiDIY can empower students with disabilities to create themselves the objects they need in their everyday life, and to better integrate in their classes (D4.1, pp. 28-30).
- Fourthly and finally, exposure to DiDIY can also help instil the concern about environmental sustainability and the idea of repairing rather than replacing that are characteristic of the maker mindset.

Two further potential advantages of getting DiDIY into education are worth mentioning. It has been argued that makerspaces in schools (which include DiDIY activities, although they are not limited to these) can help democratize learning, as they "make materials, supplies, and concepts available and accessible to all learners" (Fleming, Krakower 2016). Furthermore, MOOCs have the benefit of making top-notch educational materials available for free to everyone around the world with an internet connection and the desire to learn. They also offer flexibility and can help gifted students meet their own educational needs in cases where the schools they attend cannot properly cater to them.

3.3 Potential pitfalls of the use of DiDIY in education

That said, some also worry that the promotion of DiDIY in educational contexts might have some undesirable consequences, and one contribution of this deliverable is to consider what these might be.

We wish to stress from the start that most of these concerns only arise from an *excessive* focus on using DiDIY as a transformative factor in this context, and that the sheer promotion of DiDIY in education need not lead to such pitfalls if it is done judiciously. We would also like to explain why the upcoming discussion will, to a significant extent, tackle concerns that have to do with the possible impact of DiDIY on educational outcomes. One might wonder whether such concerns truly count as "ethical" issues, that properly belong in the present deliverable.

Our reply is twofold. First, the connection between a good education and well-being or flourishing – which are fundamentally ethical notions – has been stressed by many authors since the time of Aristotle (Kraut 2016). Education is a core determinant of people's opportunities for future employment and political participation, which are themselves of great importance for their quality of life. Furthermore, some would argue that education also directly promotes certain constituents of well-being: knowledge and understanding of the world around us, in particular. Secondly, as we will see, the impact of DiDIY on educational outcomes can in itself raise even more straightforwardly ethical issues, such as students having a fair chance to access DiDIY tools. Yet taking a stance on such issues does require prior assumptions about the educational value of DiDIY. If the introduction of DiDIY could be expected to have a negative impact on educational outcomes – a claim that we will not defend and are merely using for illustrative purposes –, it would become unclear that we ought to strive for equal access to the relevant tools. On the contrary, doing so would appear to be an ill-advised way of allocating public resources.

In what follows, we will look at four ethical concerns that might be raised about the use of DiDIY in education. While we believe that that the first three could be warranted if (and only if) DiDIY were not introduced judiciously, we will take a sceptical position towards the fourth. We will then proceed to discuss ethical issues related to DiDIY and education of a somewhat different nature: first, the use of DiDIY as a tool to attract more women into STEM education and careers, and secondly, the need to teach young people how to engage in DiDIY (broadly understood) in an ethical, responsible manner.

3.3.1 Focusing exclusively on certain aspects of education while neglecting others

The first concern that the use of DiDIY in education might arise relates to the proposal to do so for the purpose of effecting nothing short of a revolution in education (as opposed to the more modest goal of improving education by supplementing and renewing existing practices) based on the principle of *learning by making*. The concern is that this endeavour might overemphasize certain, though clearly important, aspects of education, such as hands-on learning and applied science, while neglecting others, such as more theoretical and abstract aspects of science, and even potentially entire disciplines that do not fit well into a "maker-based" model of education. Pushed to the limit, the idea of learning by making would entail that education should focus solely on teaching students how to solve concrete problems related to the production of physical artefacts, perhaps as complex as robots. The assumption made by the proponents of the model of learning by making (at least those who propose it as an all-encompassing approach to education) seems to be that, in the process of making such artefacts, students will acquire all the scientific knowledge that they need, so that, for example, in order for a student to build a robot she has to learn some principles of mechanics, electronics, control theory, computer science, and so on. But this assumption might be questioned.

First, the value of science arguably does not solely reside in the ability it gives us to solve concrete problems. This value is also significantly tied to the fact that science helps us understand the world, an understanding that has, of course, instrumental value, but is plausibly also valuable for its own sake. Quite apart from any concrete object we might produce using this knowledge, it is for example fascinating to learn the details of the theory of evolution by natural selection, or the story of how our universe formed and how it is now expanding at an accelerating rate under the influence of a mysterious factor called "dark energy". We do not wish to claim, of course, that the teaching of such topics cannot be assisted by DiDIY – say, the printing of replicas of ancient fossils, arranged in a sequence that would mimic the evolutionary process. Still, it seems difficult to imagine how such topics could be properly taught solely by getting students to make certain things, without any reliance on other tools like lectures or textbooks to convey the relevant information. And such topics certainly should not be left out of the school curriculum. Part of the role of a good teacher is arguably to stimulate her students' sense of wonder at such facts about the world, and to make them want to learn more about those facts, and about how we managed to discover them. Many of science advances are arguably owed to such a desire to understand the world for its own sake. An educational system that made the teaching of science single-mindedly focused on concrete problem-solving and left no room for such disinterested curiosity would arguably greatly impoverish the teaching of science.

Secondly, activities related to STEM subjects, such as the solving of mathematical or other intellectual puzzles, can arguably have intrinsic value even when they do not connect directly to the physical world. Mathematics provides a good example of this. Arguing in favour of the use of 3D printing in mathematics classes, Eddie Krassenstein writes that “3D printing brings a “cool” factor into a subject which could normally be quite boring” (Krassenstein 2014). While there is no doubt that inadequate teaching might result in a math class not being engaging enough, it would be seriously unfair to describe mathematics *qua* discipline as fundamentally “boring”. Mathematical concepts and reasoning can no doubt be challenging, yet mathematics can nevertheless be a truly rewarding subject if one puts in the effort to come to terms with it. There is great satisfaction, for example, in understanding Euclid’s theorem, quite apart from the practical relevance of prime numbers in cryptography (though of course such relevance should also be emphasized by a teacher to her students). While there need be nothing wrong with changing the way some STEM classes are taught so as to make them more engaging for students, it would seem problematic to completely turn teaching away from the challenges of abstract reasoning and conceptual understanding in favour of “flashy” things like those related to some new technology. Coming back to the surveys we have mentioned that assessed students’ preferences for certain types of activity at school, these preferences should certainly be taken into account as long as they do not interfere with the pursuit of core educational goals. But the pursuit of such goals should always remain centre stage, and educators should not assume that it will always fit perfectly with students’ actual preferences. Students may not always immediately appreciate what is best for them when it comes to their education.

It is true that, as some in the Maker movement are arguing, we must not “focus only on the students who are headed to college”, while “ignoring the 50 percent of those who aren’t” (Hatch 2013, p. 21). Nonetheless, all students arguably benefit from challenging themselves by exercising their abilities to solve abstract problems. It is a capacity that is likely to serve them well in our increasingly complex world, including for the sake of participating in the political process as responsible citizens. Moreover, even if we acknowledge that some students may not have a natural bent for solving theoretical, abstract problems and are more likely to flourish by engaging in more concrete forms of problem-solving, it remains that many students can learn to enjoy abstract reasoning in subjects like mathematics or physics, yet will never learn that they have this disposition unless they are given the opportunity to exercise it. This also points to the fact that different students may have different educational needs and that an educational system should, as much as possible, accommodate those differences by offering some degree of flexibility in its programs – a point to which we shall return.

Finally, while the promotion of DiDIY is particularly emphasized as a means of getting students interested in STEM subjects, some of its proponents also suggest that the use of DiDIY should move from STEM to STEAM and include the Arts and Humanities as well. The relevance of DiDIY for subjects like creative design and art is undeniable. That being said, the model of learning by making favoured by leaders of the Maker movement still seems rather inimical to most Arts subjects, since they usually do not result in the production of concrete physical objects.[2] Mark Hatch, the CEO of TechShop, reinforces that impression when he writes that “physical making is

2 They can of course ultimately result in the publication of books, which are physical artefacts, but in such cases authors are creating the *information* inside the books, rather than the physical books themselves, and therefore do not count as “makers” in the standard sense.

more personally fulfilling than virtual making" (Hatch 2013, p. 12) – the latter referring to purely informational creations such as poems, blog entries, or scientific theories.

As we have mentioned before, technologies like 3D printing could play a role in subjects like history, where they might help provide vivid illustrations of the past. D4.4 also mentions the inclusion of robotics in some history classes, as described by a representative of the Estonian Information Technology Foundation for Education in an interview with them. This is interesting and worth paying closer attention to. Yet it would seem problematic to argue that such technologies should not merely complement more traditional teaching methods but completely replace them. Besides providing a solid basis on which to rely to find the key information for a given course, history textbooks, for example, also provide students with an opportunity to solicit their own imaginations by reading narratives about the past and re-creating them in their minds – while also reflecting on the various factors that led to major historical developments. While such a process should admittedly be supplemented with exposure to concrete examples of ancient artefacts and monuments in order to maximize the accuracy of the picture of the past that students create for themselves, it would surely be undesirable to completely remove the need for students to engage in this imaginary and reflective exercise.

3.3.2 Idealizing the impact of new technologies on educational outcomes

A second concern, related to the previous one, about DiDIY in education is that the impact of new technologies on educational outcomes may previously have been overestimated, and that this should make us cautious before calling for a radical reform of the educational system based on the use of such technologies, whether associated with DiDIY or not. A relevant piece of evidence in this context is provided by a global study conducted by the OECD, titled "Students, Computers, and Learning: Making the Connection", and published in 2015. This study found, contrary to the expectations of many (who were pushing for the introduction of more technology into the classroom), that countries with education systems that involve frequent use of technology like tablets and computers tended to get *worst* results on assessments like the PISA tests[3] than countries where such devices were only used moderately in schools (OECD 2015).

One should note that this study did not measure the impact of using DiDIY tools and a maker-based model of education in schools on those test results, and we cannot assume that the same conclusions would be reached if we could get such measures (which are not yet available at this early stage in the history of DiDIY). Still, the OECD findings do show us that we ought to be cautious before proposing to radically transform education by introducing new technologies into the school system. They suggest that, rather than confidently calling for such radical reform, it might be preferable to treat the inclusion of DiDIY tools and activities into that system as a promising experiment, one that will allow us to gather more evidence about the effectiveness of that approach in improving educational outcomes – evidence that can then inform future decisions about how to shape education. Furthermore, we stress that the OECD report certainly does not warrant wholesale opposition to the introduction of new technologies in the classroom – even if it means replacing some traditional teaching tools. For example, while we have just cited some of the potential merits of textbook-based learning, there is no reason why these should not be preserved by a move to digital textbooks, which also carry the added benefit of being easier to keep up-to-date.

It is true that the methodology employed by the OECD to assess learning outcomes, such as the PISA tests, is not beyond controversy. Among other things, it has been criticized for allegedly

3 PISA stands for "Programme for International Student Assessment".

failing to take into account all the relevant aspects of student learning, and for reaching arbitrary results that overly depend on specific kinds of question choice or weightings (Chalabi 2013). In a similar vein, leading figures of the Maker movement like Dale Dougherty questioned the idea that standardized tests of the sort which organizations like the OECD tend to rely on measure "true" learning (Dougherty 2012). As we have mentioned, Dougherty has proposed the idea of making as a supposedly superior criterion of learning, and he would certainly object to the idea of assessing the effectiveness of the learning by making approach by using PISA results as a metric.

Offering a confident overall assessment of the methodology behind the PISA tests is an extremely ambitious endeavour that lies beyond the scope of the present deliverable. It would require not only surveying all the relevant empirical data, but also articulating a comprehensive philosophy of education, since people with different philosophies might reach different conclusions about the value of a particular educational system even while relying on the same empirical evidence. Here we will confine ourselves to noting that the adequacy of the OECD method of assessment based on the PISA tests is a matter of controversy. We are not in a position to confidently endorse it, but neither can we assert that any proposed alternative to it would indeed be superior, as we are not familiar with any persuasive argument in support of such an alternative. Dougherty, at any rate, does not offer such an argument to defend his model of learning by making. He simply asserts that his criterion of learning is the better one. Yet we can think of various ways in which that criterion appears insufficient.

- To begin with, it seems to be biased against all disciplines that do not fundamentally involve the making of physical objects: this would include pure mathematics, history, geography, philosophy, English and other languages, as well as sociology and psychology (in cases where they are taught at the secondary school level). If all learning is to be assessed by reference to the production of physical artefacts, then the subjects just cited do not involve any true learning (or at best very little of it, e.g., in cases such as history students printing replicas of ancient artefacts), a clearly absurd implication.
- As a counterpart to this, leaving aside all subjects that are not clearly connected to making would entail that students might complete compulsory education without properly acquiring fundamental linguistic and critical reasoning skills that are crucial for their future careers and for their lives as citizens.
- Finally, even for disciplines that are clearly relevant to the process of making, such as maths or physics, it is at least not self-evident that making alone will suffice to provide children with the basic knowledge and skills they will need in those domains: to come back to a point we made previously, we may wonder to what extent a maker-based model of education will help develop a student's capacity for abstract reasoning – a capacity that is just as relevant to STEM jobs as creativity is, according to experts writing for the OECD Skills and Work blog (Vandeweyer 2016). In short, even if one is dissatisfied with the methodology underlying the PISA tests, it is questionable that simply replacing it with the model of learning by making would be an adequate solution.

It is worth noting here that, according to D4.4, there is still some resistance among teachers to the introduction of DiDIY into education, as reported by several of the European stakeholders whom they interviewed. On that basis, it might be argued that the calls from leaders of the Maker movement to radically reshape the educational system, even if they are not backed up by the available evidence pertaining to learning outcomes, are nevertheless justified in light of that resistance to change. In other words, in the face of an overly conservative school system, we ought not to fear pushing too hard in the direction of change, since we cannot expect such calls for change to be fully heeded anyway. While this raises an interesting issue about the best strategy to adopt to foster positive change in this context, it would seem, first, that questions about political strategy should be kept distinct from questions about what the best educational practices for the 21st-Century actually are (and in this deliverable we are focusing on the latter); and secondly, it is at least not obvious that calling for radical change in the absence of conclusive supporting evidence is the approach most likely to convert those who are sceptical about the desirability of such change.

3.3.3 Promoting a "one size fits all" approach to education

One of the proposals advocated by those pushing for a revolution in education based on the use of DiDIY concerns the move towards teamwork in the learning context: the idea is to promote a "project-oriented, team-based education" (D4.1, p. 17). Associated concepts involve collaborative learning and the flipped classroom. In this vein, a report on the impact of the Maker movement produced from the Maker Impact Summit from December 2013 emphasizes the idea of "collaboration" in learning, which it says "relieves the learner from isolation, fostering a learning disposition that is also fuelled by connectedness" (Deloitte Center for the Edge and Maker Media 2014, p. 19). These are certainly promising ideas, and there is already some evidence of the educational benefits of the flipped classroom approach (e.g., Gross et al. 2015; Webb, Doman 2016). The key question here is how exactly one is proposing to implement those ideas. When key figures of the Maker movement propose to radically re-shape education around such principles, one might start worrying that their project might unfairly disadvantage students with certain learning styles, by introducing a "one size fits all" approach to education – paradoxically one of the very reasons for which advocates of a maker-based education are criticizing the current system. One relevant social group here is introverts. For instance, Michael Godsey writes (2015) in *The Atlantic* that:

> The way in which certain instructional trends – education buzzwords like "collaborative learning" and "project-based learning" and "flipped classrooms" – are applied often neglect the needs of introverts. In fact, these trends could mean that classroom environments that embrace extroverted behaviour – through dynamic and social learning activities – are being promoted now more than ever. These can be appealing qualities in the classroom, of course, but overemphasising them can undermine the learning of students who are inward-thinking and easily drained by constant interactions with others.

Once more, the worry here depends on the specific extent to which one wishes to re-shape the educational system in accordance with these principles. Some degree of teamwork in education can arguably benefit everyone and help build useful social and collaborative skills. But beyond a certain degree, the emphasis on group work can become harmful to introverted students, who might learn better if given enough time to quietly study and reflect on their own before discussing their ideas with others. Godsey's article, as well as the work of authors like Susain Cain (see, e.g., Cain 2012), suggests the existence of a trend in contemporary education that neglects the needs of introverts, despite the fact that they represent between one third and one half of the total population. Pushing for a model of education that emphasizes collaborative and project-based learning without reflecting carefully about the possible differential impact of such a model on students with different personalities and learning styles might exacerbate this negative trend.

Let us emphasize again that these first three concerns only arise on the assumption of a radical and systematic transformation of existing practices following a particular maker-based model of education, advocating a specific way of using DiDIY in the educational context, centred around the idea of making physical artefacts. They do not apply to a more moderate approach that seeks to implement that model in contexts where it seems most promising, that treats it as an educational experiment rather than a silver bullet (at least as long as solid evidence of its efficacy has not been produced yet), and that ensures an appropriate degree of flexibility in class activities and teaching methods to adapt to the individual needs of students.

3.3.4 Neglect of traditional manual (craftsmanship) skills

Another concern that might be raised about the introduction of DiDIY activities into the educational context would be that it might cause traditional "making" skills to no longer get developed among new generations, because the digital aspect of DiDIY would make those skills obsolete. For example, the use of digitally-driven laser cutters to engrave or cut decorative shapes in materials like wood removes the need for the manual skills that would previously have been required to produce such artefacts. First, some might lament the expected loss of such skills and argue that DiDIY will cause the "makers" of the future to become designers, rather than true makers or craftspeople. Secondly, one might worry that introducing very young students to DiDIY might have negative consequences for them, insofar as relieving children from the "burden" of crafting things – by delegating this task to 3D printers and other technological tools – could potentially limit their cognitive development, which has been proven to be connected with manual manipulation (Grissmer et al. 2010; Cameron et al. 2016).

Taking these two arguments in turn, it seems to us that the first one has, at best, only limited force. For one thing, while the advent of DiDIY tools like laser cutters or CNC mills does seem to reduce the need for some of the traditional craftsmanship skills, it is not clear that it must remove it entirely. For example, some school projects focused on making could allow for the use of DiDIY tools, while others might explicitly require students to use traditional methods to cut the relevant materials in the desired shape. Even when the use of DiDIY tools is allowed, some parts of the making process might not allow for automation: the student might use a laser cutter to cut wood yet might still need to put the finishing touch to her object by hand (say, for the rubbing out phase), and so on.

For another thing, even assuming that the introduction of DiDIY in education would indeed largely replace traditional craftsmanship skills, it is unclear that this *by itself* constitutes a persuasive objection to its introduction. Those who value such skills may reasonably regret such a development, but having reason to regret the disappearance of a certain practice does not entail being morally obligated to take steps to prevent its disappearance. DiDIY would be no different in this respect from the many other cases in history in which a new transformative development rendered the use of certain skills less relevant. For example, children who regularly travel to school using school buses might be less likely to perfect their cycling skills. Nevertheless, this is not seen as a reason to prohibit the use of school buses. The loss of some degree of cycling skills due to less frequent cycling practice may constitute an acceptable trade-off for the sake of the additional safety, convenience and conviviality (meeting up with friends) that school buses provide, to which it should be added that cycling skills can still be practised on independent occasions if the child so wishes.

The second argument, however, does have greater force than the first one. If the introduction of DiDIY among young students could compromise their cognitive development, this would clearly be cause for concern. However, some of what we just said in response to the first argument points to a way of addressing that concern. Granting that the honing of manual skills is an important contributor to that development, the implication is that schools should organize their curriculum so as to ensure that it makes appropriate room for activities involving manual manipulation. This could mean introducing DiDIY activities gradually, in accordance to children's developmental needs as indicated by the best available evidence, and retaining activities that promote more traditional skills of craftsmanship, and also bearing in mind, as we have mentioned above, that not all activities involving DiDIY render such skills unnecessary.

3.3.5. Producing unnecessary extra waste

Some of the proposals that have been made for introducing DiDIY in education would involve the production of many additional physical artefacts. For example, as we have previously mentioned, some advocate using 3D printing to make the teaching of various school subjects more appealing (Krassenstein 2014):

> Imagine if every history class had the ability to 3D print replicas of artefacts from a massive library of downloadable STL files. Every classroom would now have access to museum artefacts from the luxury of their own school.

Krassenstein also mentions that the authors of geology textbooks could "include files for 3D printable models with each chapter in their books", and that 3D printing physical models of mathematical objects could help students who have difficulties understanding certain mathematical concepts. In fact, according to Krassenstein, "just about every subject within a school curriculum could benefit from 3D printing technology" (ibid.). In response to this type of proposal, however, some people – including some of the stakeholders interviewed for D4.4 – have raised the worry that getting students to regularly make artefacts on an individual basis, using DiDIY tools like 3D printers, as part of the school curriculum might lead to a waste of resources including time, energy and printing materials.

It seems to us that this worry can be partly alleviated by pointing, first, to the existence of devices, like the ExtrusionBot Cruncher, that can recycle certain plastic items, including old 3D prints, into fine plastic which can then be extruded into useable filament (Molitch-Hou 2015). As long as such devices were available to students and as students could be taught to use them to recycle their old prints rather than throw these away, the risk of creating large amounts of extra plastic waste would be limited. Secondly, as long as DiDIY manufacturing were used in a judicious manner that benefited the learning process, it would be inappropriate to speak of resources simply being "wasted" in that context. Still, while this reply does show that this worry clearly cannot justify keeping DiDIY manufacturing out of education, it does not mean that it has nothing valid to tell us. Arguably, educators should seek to strike the right balance between exploiting the fun factor associated with DiDIY manufacturing and limiting their schools' expenditure of energy (and potential creation of some amount of plastic waste). When similar educational outcomes can be achieved using an alternative to DiDIY manufacturing, for example by taking students to museums where they might examine actual fossils, or by using one set of printed replicas kept in the school and re-used by all teachers for all of their classes, there at least be a reason to prefer the alternative if there is good evidence that it is more environmentally-friendly.

3.3.6 Aggravating educational inequalities

As we have previously mentioned, it is still too early to tell, based on quantifiable evidence, whether the introduction of DiDIY in schools leads to an improvement in educational outcomes. However, suppose that it does in fact have that effect. The concern then arises that schools (or possibly larger entities like countries) that are more favourably inclined towards DiDIY, or that enjoy a better financial situation allowing them to set up appropriate facilities and to train teachers appropriately, will provide better educational opportunities to their students than more conservatively-minded or financially less advantaged schools. Students at the latter schools will then, through no fault of their own, find themselves at a disadvantage in their educational and, ultimately, professional and socio-economic opportunities. Even worse, existing educational inequalities – which in countries like the United States, disproportionately affect students from ethnic minorities – could get compounded by such a development. This would clearly be a regrettable and unfair state of affairs.[4]

This concern certainly seems warranted, even though it would not be fundamentally novel. Inequality in educational prospects resulting from certain schools being better than others, often because they are also financially better off, is a long-standing problem in many countries, such as the United States or the United Kingdom. In wealthy neighbourhoods in the US, for instance, districts collect more property taxes, meaning that they have more money to fund their schools, which translates into better educational opportunities for the students at those schools (O'Donnell 2015). And in the UK, it has long been the case that the chance to attend a private rather than a public school, which mostly depends on one's family's ability to pay, confers significant advantages with regards to one's future professional opportunities, thus contributing to social inequality (Green et al. 2010). Of course, the fact that such undeserved inequalities are well-known does not diminish in any way the need to take steps to remedy them if we can, and such steps would be equally called for if some students were to get a lower-quality education because their schools were either financially unable or reluctant to incorporate DiDIY as part of its programs. Measures that policy-makers might consider to address this issue, if it were to arise, include re-thinking their way of allocating educational resources so as to support disadvantaged schools (which itself could require other reforms, e.g., involving taxation) and introducing regulations that would compel recalcitrant schools to make adequate room for DiDIY, for example by setting up suitably equipped Fab Labs or makerspaces within their premises.

So far, we have been focusing on educational inequalities that might result from the differential availability of DiDIY within the school system. Some might worry that such inequalities could also arise from different children having unequal access to DiDIY tools at home, again either because of the attitudes or the economic situation of their parents. Governments would have fewer direct means of addressing such a problem if it were to arise, aside from adopting economic measures that would favour lower-income families. Luckily, this problem is still entirely speculative given the current state of the evidence.

4 Some might view inequality of access to DiDIY tools and activities as unfair regardless of its impact on educational outcomes, appealing for example to the contribution of DiDIY to personal fulfillment. While such a line of argument can certainly be pursued, it seems to us that correcting any such unfairness would seem less urgent than if we do posit a negative impact on educational outcomes, including STEM literacy.

Having looked at some of the potential pitfalls of the introduction of DiDIY in education, we now turn to two other ethical issues that no longer bear on the negative consequences that that development might have.

3.4 DiDIY as a tool to attract more women to STEM subjects and careers

D4.1 suggests "evaluating if and how DiDIY could attract more women to STEM classes and faculties". Indeed, women are one key group who are significantly under-represented in this context, compared to their proportion of the global population (other groups include ethnic minorities such as African Americans and Latinos in the US; while our discussion will be focused on women, our conclusions should be broadly applicable to those other groups as well, although in their case economic disadvantage becomes an additional salient factor, bringing us back to the previous subsection). The World Economic Forum (2016, p. 38) mentions for example that "in STEM education, women currently make up only 32% graduates across the world". This is viewed by many as a serious concern that needs to be addressed promptly.

From the perspective of an ethical analysis, we need to ask why exactly this gender imbalance in STEM fields should be viewed as problematic. The answer might initially seem perfectly obvious: it is a sign of sexist discrimination against women in those fields, which is unjust. Nevertheless, while we agree it is reasonable to worry that such imbalance might constitute evidence of discrimination, reaching a conclusion on this issue is not as straightforward as it might seem. The reason is that equality of *opportunity*, which is arguably what really matters from the point of view of fairness in this context, does not automatically entail equality of *outcome*. As a number of authors, including some prominent feminists, have pointed out, it is conceivable that the unequal representation of men and women in STEM fields could, at least in part, result from the two genders tending to make different educational and career choices, based on different preferences, rather than being solely attributable to discrimination and sexist social conditioning (e.g., Sommers 2009; Levy, Kimura 2009). Some of these authors also remark that women do express greater interest in certain STEM sub-disciplines, such as the biological sciences, than in others like the physical sciences and engineering, and that they are represented in greater numbers in the former. They then go on to suggest evolutionary explanations for such differences in the preferences of women and men (see, e.g., Levy, Kimura 2009, pp. 248-50).

This is undoubtedly a very controversial issue. Other authors argue, to the contrary, that the unequal representation of women in STEM fields is primarily caused by negative gender stereotypes, bias, and a working environment that is inhospitable to women (e.g., Spelke, Grace 2007; Busch-Vishniac, Jarosz 2007; Barnett, Sabatini 2009). We will not take a firm stand on this debate here, even though we are inclined to believe that all of the above mentioned factors, rather than just one in particular, are likely to be implicated in creating the gender imbalance observed in STEM fields. We will point out, however, that DiDIY would seem to have greater relevance as a possible solution here if we assume that the differences in educational and career choices made by the two genders – for reasons *other* than sexist socialization – explain at least part of that gender imbalance. Indeed, if we assume that discriminatory factors provide all or almost all of the explanation of the imbalance, then it becomes unclear what positive difference the promotion of DiDIY in education could make. If there is pervasive anti-female bias in STEM fields, including STEM education, and if the environment in those fields is to some degree hostile to women, why should not we expect the same problems to surface in DiDIY contexts?

In fact, deliverable D4.4 mentions that, according to most of the stakeholders interviewed for that deliverable, the DiDIY-centred classes and activities that are currently being run still see men attend in greater numbers. If this is again to be explained by sexist influences, then sexism needs to be tackled within DiDIY itself. There are various ways in which this could be done: they include encouraging women, e.g., through awareness-raising events, to take lead roles in contexts like Fab Labs and become role models for other women (*ibid.*). This measure is actually applicable beyond the DiDIY context, to combat sexist discrimination in STEM fields more generally (e.g., encourage applications from women for science teaching positions). Other relevant more general measures include advocating for equitable performance evaluation processes, not subject to sexist bias, instituting mentoring and career-developmental programs for women, and promoting a flexible work culture that allows women to fulfil their desire to raise a family without having to renounce their goal of a career in STEM (Barnett, Sabattini 2009). The basic point here is that we cannot expect to counter sexist influences – and unequal gender representation, to the extent that it is the result of such influences – in STEM fields simply by promoting DiDIY in education.

On the other hand, if the gender imbalance in STEM fields is at least to a significant degree the result of men and women having different preferences and making different choices in terms of their educational and career paths, the promotion of DiDIY might become of greater relevance, if involvement in DiDIY activities tends to make STEM, or possibly STEAM, subjects more appealing to female participants than other potential ways of teaching those subjects. To the best of our knowledge, it is still too early to tell whether that is indeed the case on the basis of the available evidence (though some suggestive evidence does already exist).[5] Here again, it therefore seems advisable to treat the promotion of DiDIY in education as a valuable experiment, which will yield new quantifiable evidence about the most effective ways of getting women interested in STEM. It can be one important element in our toolbox, alongside others: Stephen Ceci and Wendy Williams suggest that in order to correct the misperceptions that some students, including female students, might have acquired about fields like engineering, physics, or computer science, we should "expose students to information about a range of career options in STEM fields so they fully understand the career possibilities when they begin their implicit cost-benefit analysis of which careers are worth what level of effort and delayed gratification" (Ceci, Williams 2007, p. 221).

Here, however, it might be objected that, to the extent that the gender imbalance in STEM is due to the differential autonomous choices made by men and women in terms of education and career, this imbalance can no longer be regarded as unfair, and therefore that the ethical imperative to correct that imbalance disappears. While agreeing with the former claim about fairness, we disagree with the latter. Arguably, even if we leave possible sexist influences aside, there is still a good reason to encourage more women to get involved in STEM fields – though one that is distinct from considerations of justice. As we have mentioned earlier, much of the job creation in the coming decades is expected to occur in STEM jobs families, a fact recognized for instance by the European Parliament in a study published in 2015 (Caprile et al. 2015; see also World Economic Forum 2016). Even though young people, both men and women, should certainly have the freedom to decide for themselves what professional trajectory they wish to embark on, encouraging them to

5 For example, the company Techbridge, which runs after-school programs focused on hands-on learning involving tools like 3D printers and Arduino electronics, surveyed 367 girls who had participated in its programs and found that nearly 90% reported having developed an increased interest in STEM as a result of the program (National Research Council et al. 2014).

develop the sort of skills that are especially likely to help them make the most of upcoming job opportunities, thereby also fostering economic growth, certainly seems like a worthy social goal.

3.5 The need to teach students how to use DiDIY ethically

Before concluding this section of our deliverable, let us say a few words about an issue highlighted by some of the stakeholders interviewed for D4.4, namely, the need for ethics education for students who use digital tools like social media, for instance, and might sometimes either engage in or become the victims of undesirable activities like cyberbullying. The unfortunate phenomenon of cyberbullying is now a familiar one, mostly in compulsory education contexts, but also to some extent at the college level. Here, let us note, we are no longer talking about an ethical issue raised by the introduction of DiDIY in education. Rather, the topic is the education of young people on how to use certain DiDIY tools responsibly and ethically. The use of social media, such as blogs or social networks like Facebook, for non-professional purposes does count as DiDIY according to the broad definition based on the Knowledge Framework that we have outlined in an earlier section of this document.

Various such strategies on how to prevent behaviour such as cyberbullying have already been proposed by experts in the field. They typically agree that education – coupled with early identification of aggressors and their victims – is preferable to legislation for that purpose (Mahoney 2013). Such education could be part of a broader program of teaching "digital citizenship" to young people, a program that would tackle a number of different issues beyond cyberbullying, such as digital privacy, internet safety, and online plagiarism. A growing amount of resources is available on the internet to help teachers who would like to offer classes on such topics (see, e.g., Krueger 2014).

3.6 Conclusions on DiDIY in education

Based on our discussion so far, we can propose the following conclusions regarding the ethical issues surrounding DiDIY in education.

- As explained in other deliverables for this Project, the introduction of DiDIY activities (such as building robots and other similar artefacts using DiDIY tools, in the context of a Fab Lab or a makerspace) in compulsory education can enrich the curriculum and teach valuable new skills to children. The introduction of makerspaces in schools, equipped with state-of-the-art digital devices, and of classes focused on DiDIY-related activities is a trend to be promoted.
- In light of the recent mixed evidence (e.g., PISA results) regarding the impact of the introduction of technology in schools, policymakers might want to show caution before endorsing the proposal to "revolutionize" education advocated by radical figures within the Maker movement, which would involve ditching traditional teaching methods and standardized testing to focus instead entirely on principles like DiDIY and learning by making. These activists may well be right that current educational practices neglect certain categories of students and certain aptitudes like hands-on skills, and therefore that reforms are called for. That said, in the course of implementing such reforms, we may want to avoid replacing one excess with another.
- A more nuanced approach would involve promoting DiDIY in suitable sectors of education as an experiment, and using the process to gather data about DiDIY impact on educational outcomes that can help guide future policy, to ensure that such policy is based on evidence

rather than ideology. Ideally, this experiment should be conducted in a spirit of flexibility that respects individual differences in educational needs and preferences between students. It can also be implemented alongside other promising reforms destined to further the core goals of education to be in the 21st-Century. This general approach might be encapsulated in this quote from two activists for the Maker movement who, in a discussion of its relevance to higher education, write that "academic makerspaces provide participatory contexts for hands-on, fun and collaborative learning that are a refreshing alternative – albeit no substitute – to "sage on the stage" lectures" (Henseler, Rieffel 2014).

- When it comes to higher education, MOOCs are a trend worth encouraging, given the power they have to democratize learning around the globe – though whether or not to offer such courses obviously remains the prerogative of individual academic institutions, especially given their reliance on the principle of open access.
- The possibility that the rise of DiDIY in education might potentially lead to a loss in traditional craftsmanship skills is in itself not weighty enough to warrant combating or slowing down that development. Nevertheless, when introducing DiDIY into the curriculum, schools should bear in mind the importance of helping young students develop the manual skills that have been shown to be connected with cognitive development.
- The fact that the unequal availability of DiDIY activities in different schools could potentially exacerbate existing inequalities in the standard of education that students receive provides policy-makers with an additional reason to pay attention to those inequalities and to promote progressive policies that support schools facing financial challenges. If new evidence emerges confirming the efficacy of DiDIY in education, they should also be ready to put pressure on schools with a more conservative attitude to DiDIY to keep up with the trend.
- When it comes to addressing the under-representation of women in STEM fields, the promotion of DiDIY in education cannot by itself be expected to resolve the gender imbalance if we assume that it is, at least for the most part, caused by sexist forces like gender stereotypes. To address such forces, separate measures are needed, and they should be implemented within the DiDIY context itself. However, to the extent that the imbalance is caused by differences in the autonomous choices made by men and women when it comes to their education and career paths, DiDIY is worth exploring as one possible tool to try and generate more excitement for STEM fields among young people, including women and other under-represented groups.
- Classes in digital citizenship should be promoted to help young people learn to engage in DiDIY responsibly and ethically.

4. DiDIY in research

4.1 Introduction

Having considered the ethical issues raised by the introduction of DiDIY in education, we now turn to the other side of this deliverable, DiDIY in research. As we have mentioned at the start of this document, following D4.1 the extent to which DiDIY is currently being applied in research, or is expected to be, is less obvious than in the educational contexts. Digitally-driven devices like 3D printers, a paradigmatic example of a possible DiDIY tool, are indeed used in some of current most exciting developments in biomedical research, such as 3D bioprinting, an application of 3D printing (which we will discuss at greater length in what follows in order to expand the scope of our ethical analysis in this document) used to create tissues for research purposes, and even more ambitious structures like organs. Nevertheless, this new digital technology is typically being used in a professional context, by researchers funded by grants and/or their academic institutions, something that, according to the way we are characterising it, cannot be considered DiDIY.

Still, DiDIY does have relevance in the research context. First, an increasing number of professional researchers take advantage of the opportunity to build their own research equipment at an affordable cost, thanks to the rise of tools like the RepRap 3D printer (which can print most of its own components) and open-source Arduino microcontrollers, as well as websites like Thingiverse (Pearce 2012; Doyle 2012). Even though these people end up using the relevant devices as part of a professional endeavour, they nevertheless build them themselves (and a digitally-driven device is involved either as the end product or as the tool used to make that product, and both are often the case), as opposed to purchasing them from commercial channels, as has been the standard practice so far. Secondly, the rise of DiDIY tools has also made it easier for amateurs to get involved in scientific research, as illustrated by "DIY biology" (Kellogg 2012). They can do so either at home, by purchasing their own equipment, or by joining a "DIY lab" such as Genspace in Brooklyn, New York, and Biocurious in Sunnyvale, California, that will provide them with lab space and appropriate equipment, against the payment of a memberships fee (*ibid.*). Furthermore, we may also want to distinguish between amateur scientists, who conduct their own experiments and lead their own research projects independently but are simply not doing so as paid professionals, and "citizen scientists", a term standardly used to refer to laypeople who contribute to existing research projects (e.g., by helping collect data) under the supervision of the professional scientists who run the projects in question (Resnik et al. 2015). DiDIY tools could in principle be used by both amateur scientists and citizen scientists.

In the following two sections we will look in turn at the benefits of these ways of introducing DiDIY in research, and at the potential ethical issues that they raise.

4.2 The benefits of DiDIY in research

The first benefit of the availability of DiDIY in the research context is that, as just suggested, it allows both professional and amateur scientists to have access to research equipment, by making it themselves, at a much lower price than would otherwise be possible.[6] In the case of amateurs, this means the chance to conduct research that they would not have been able to carry out otherwise; in

6 Equipment that can itself accelerate the pace of research in some cases, such as when it comes to producing a series of prototypes for robotics research (Campbell 2011).

the case of professional researchers, it means at least the ability to save significant amounts of money (some articles mention thousands of dollars, e.g., Wolf 2013), which sometimes can again make the difference between a research project being carried out or not, in a context where research funding from traditional channels is usually scarce and difficult to secure (*ibid.*).

The second benefit is a direct consequence of the first: if DiDIY allows more people to engage in research projects by broadening access to the right equipment, it increases the chance that scientific breakthroughs will be made in the future, since more people will be participating in the scientific enterprise. While this should be self-evident in the case of professional researchers, the contribution of non-professionals should not be neglected. A number of amateur scientists do possess a formal scientific background, but may be employed outside academic institutions and pursuing research during their spare time; furthermore, advocates of DIY science argue that those without formal qualifications can bring a fresh perspective and new talent to the scientific enterprise, and more generally that amateur scientists enjoy the freedom to pursue more audacious research projects than risk-averse funding bodies might be willing to support (Kellogg 2012; Griffiths 2014).

4.3 Ethical concerns about DiDIY in research

The most salient ethical issue that arises in relation to the use of DiDIY in research is probably *safety*. To the extent that the concept of DiDIY suggests that the research in question occurs outside the professional context, one might worry that the safety precautions taken to conduct that research will be less stringent, potentially allowing dangerous materials or substances to get created, which if released, either intentionally or by accident, could cause damage to public health, the environment, and the economy (Kellogg 2012). At one extreme, some fear that the advent of tools like 3D bioprinters (a category of 3D printers with the ability to build biological structures, which we will discuss in more detail in subsection 4.4) might allow amateur scientists working in the field of synthetic biology to create dangerous pathogens, which could even be used as weapons of mass destructions by would-be terrorists (Dvorsky 2014). On a related note, Jason Lee, a specialist on science and technology-based threats for the FBI, was quoted as stating that “terrorists and violent criminals could use do-it-yourself techniques [including regular 3D printing] to mould ordinary-looking objects as hollow shell decoys to conceal explosives, toxic chemicals or other materials that can cause harm” (Lane 2014). The question of how seriously we should take such concerns is addressed in D6.2.

Beyond safety, citizen science has been said to raise ethical concerns of its own, and these could in principle apply to cases involving DiDIY. Resnik and colleagues list four types of ethical concerns relevant to citizen science (Resnik et al. 2015).

- *Data quality and integrity*. This is the concern that the data collected by citizen scientists may not meet adequate scientific standards. Resnik and colleagues suggest various strategies to address this issue, including providing citizens with appropriate training and reviewing and auditing data during the collection phase.
- *Data sharing and intellectual property.* It is important that the data collected by citizen scientists should be shared with the public once a scientific study has been completed, while such data should not be released prematurely, before appropriate reviewing has taken place. Resnik and colleagues argue that investigators should set clear expectations with citizen scientists on this issue. Furthermore, they also mention that citizens and local communities may sometimes “assert ownership over the information that has been gathered and expect to

have some control over how it is shared and used" (*ibid*., p. 478). In response to this issue, they argue that "scientists who work with citizens should clearly discuss data ownership and other intellectual property issues with citizen volunteers at the beginning of the project, and periodically and as needed, to ensure mutual understanding" (*ibid.*).

- *Conflicts of interest.* These can arise for instance when citizen scientists have relationships with private organizations that sponsor research and pursue, say, a certain political agenda. Strategies to address this issue include disclosure by the citizen scientists concerned of the relevant conflicts of interest, and making data publicly available after publication so that the data analysis and interpretation can be independently evaluated (*ibid.*, p. 479).
- *Exploitation.* The concern here is that citizen scientists might not be treated fairly in the context of their contribution to a scientific study, for instance "if lay-volunteers or local communities do not receive a fair share of the benefits of research" (*ibid.*). Resnik and colleagues' response is simply that scientists should offer citizens a fair share of those benefits, which may include ownership of intellectual property, authorship recognition on publications, or financial compensation.

While such ethical issues may also arise in cases of citizen science involving DiDIY, there seems to be no reason to think that the introduction of DiDIY in citizen science would itself reinforce, or even contribute at all to the emergence of any of those issues. In fact, DiDIY might on the contrary help alleviate the first two concerns. First, digitally-driven tools might facilitate a more accurate collection of data; and secondly, as mentioned in other deliverables for this Project, the DiDIY community tends to favour the free sharing of information, which means that disputes over intellectual property are less likely to arise among people with a DiDIY mindset.

5. DiDIY uses of cutting-edge research

Our analysis so far has suggested that the use of DiDIY in research does not raise a large number of ethical concerns. For the most part, it rather seems to promise interesting benefits. However, further issues present themselves if we extend our discussion beyond the theme of DiDIY in research, to consider possible forms of DIY that make use of digitally-driven devices that are the products of the latest research in engineering and the biomedical sciences (the devices in question are often themselves being used to pursue further research). Relevant examples include regular 3D printing, 3D bioprinting, and devices implanted under a person's skin. In what follows, we begin by considering the DIY use of such technologies for therapeutic purposes. We then move on to describe their possible uses for non-therapeutic purposes, which are more controversial and therefore a more fertile source of ethical concerns. We end this section by looking at these ethical concerns – relating to both therapeutic and non-therapeutic uses – in turn.

5.1 DiDIY uses of cutting-edge research: therapeutic applications

Cutting-edge developments in 3D printing represent a promising source of DiDIY applications for therapeutic purposes. For instance, 3D printing technology makes it possible for people who have lost a limb and need a prosthetic replacement to make one themselves, for only a fraction of the cost they would have to incur if they were to get it from a healthcare provider (Fichtner). Furthermore, the prosthesis can be tailor-made to the person who needs it, and new updated versions can repeatedly be created if necessary, for example if the recipient is a child still growing up (*ibid.*). Another case in point, which was touched on in D3.3, is the home printing of customizable drugs, which some expect to constitute a great step forward for personalized medicine, allowing for cheaper, more accurate, and more effective medications.

A related, relevant development is 3D bioprinting, an emerging technology that relies, as its name indicates, on the principles of 3D printing. Just as 3D printers build various objects by depositing basic materials of all kinds (from plastic to metal) layer by layer, 3D bioprinting is a process that involves depositing, layer-by-layer, living cells on a pre-shaped supporting scaffold, with input from a computer-aided design (CAD) file, in order to build biological structures such as tissue, bones, and, in the future (it is hoped), whole organs (Varkey, Atala 2015).[7] In this respect, 3D bioprinting is certainly one of the most fascinating and promising technologies for digital manufacturing that are currently being developed. Many anticipate that it will not only help alleviate the current serious problem of the shortage of organs available for donation, by allowing us to manufacture organs on demand, but that it will also allow to drastically reduce, if not eliminate, the issue of organ rejection (by the recipient's body), since the technology should allow tailor-made organs to be grown from the recipient's own cells (*ibid.*).

From the perspective of the present discussion, 3D bioprinting is relevant not only because it is currently still at the research and development stage, but also because one promising area of application for this technology is biopharmaceutical research and development, and more specifically 3D bioprinted tissue models that could be used for drug discovery and toxicology

7 It may be worth noting here that the actual printing process only takes us so far as the deposition of cells on the scaffold, after which the scaffold is dissolved and the cells organize into the desired biological structure based on their own natural properties (Kamen 2015). For the sake of simplicity, we will simply speak here of "organ printing" to refer to this entire process, yet we do not thereby wish to suggest that the process involves a fully ready organ just "popping out" of a printer.

testing. According to Varkey and Atala, this application of the technology is aimed "at replacing animal testing of new drugs and enabling safer and more effective delivery of new drugs to the market at a much faster rate and lower cost" (*ibid.*, p. 278).

What DiDIY applications of 3D bioprinting can we expect in a therapeutic context? Jasper Tran envisages one in the context of organ transplantation: he thus writes that "an individual recently diagnosed with lung cancer could simply print another compatible lung from her home bioprinter and have a doctor replace her current lung with this new lung" (Tran 2015, p. 129). One may, however, ask who exactly would be motivated to print a replacement organ at home (even if medical professionals were then involved to perform the transplant), rather than relying on the public or private health care system, which could be expected to provide better guarantees of quality when it comes to the printed organs.

In reply, a first possible candidate would be people who, for whatever reason, found themselves out of reach of any properly equipped medical facility, and urgently needed an organ transplant. Soldiers in war zones have been cited as a relevant example in this regard. While we would typically still be dealing with groups of people printing the organs (or prosthetic devices) they needed on the spot, it would nevertheless seem appropriate to regard this as DiDIY, insofar as the soldiers in such a group would be building the artefacts themselves (what was referred to as "group-level DiDIY" in D3.3), rather than purchasing them from a company or obtaining them from a medical facility. Organs produced in this DiDIY manner could help save many lives in times of conflict and other harsh circumstances. On a less positive note, a second candidate would be owners of a bioprinter who sold home printed organs for transplantation on a black market, to people who could not obtain the organs they needed otherwise. While we may hope that such a black market will hold little appeal in Western countries, where printed organs might become widely available within the healthcare system once the technology gets perfected, developing countries might unfortunately be at greater risk of experiencing such a phenomenon (Wordsworth 2016).

A final example, still involving 3D bioprinting, concerns the fast distribution of vaccines around the world. Noted biotechnologist Craig Venter thus suggested that 3D bioprinters could be used to better disseminate vaccines – which could be printed on the basis of an emailed set of instructions – in urgent situations, such as a novel pandemic or bioterror attack (MacKenzie 2012).

5.2 DiDIY uses of cutting-edge research: non-therapeutic applications

Besides their projected therapeutic applications, the technologies just described (as well as other cutting-edge developments that might be put to DiDIY use) can in principle also be used in pursuit of non-therapeutic goals. Such goals include *human enhancement*, and others besides it. In the coming subsection, we will undertake to clarify the distinction between therapy (or treatment) and enhancement, before providing illustrations of various types of non-therapeutic applications of DiDIY in the next subsection.

5.2.1 The treatment-enhancement distinction

A key notion when it comes to discussing the use of some technological intervention for non-therapeutic purposes is the distinction, well-known in the applied ethics literature, between treatment and enhancement (the treatment-enhancement distinction, henceforth abbreviated TED). The TED has proven highly influential, and is often appealed to for the purpose of drawing an ethical line in relation to biomedical interventions. A radical view, rarely put forward in the literature, would state that while treating disease is ethically sound and lies within the proper bounds of medicine, enhancements are always ethically problematic and constitute a distortion of the medical enterprise. More common is the more moderate view according to which enhancement constitutes a “boundary concept” that can “help define the social role of the medical profession, demarcate the proper sphere of biomedical research, and help set limits on health care payment plans” (Juengst 1998, p. 29; see also Daniels 2000 and 2008).

How exactly is the TED to be understood? A common avenue taken by those who wish to use the distinction to serve as an important ethical boundary is to define treatments as interventions that improve human traits or capacities so as to restore or maintain health. Enhancements, by contrast, are characterized as interventions that go beyond this goal by improving the traits or capacities of already healthy people, thereby making them “better than well” (see again Juengst 1998). It is worth noting here that the way the TED is used by its proponents often seems to imply a strict dichotomy between treatments and enhancements as mutually exclusive categories. However, it has been argued that such a dichotomy is untenable, given that technological interventions can sometimes be used in ways that count as both treatments and enhancements, even on the basis of the definitions just given (Erler 2016); some of the examples we will consider actually illustrate this. Nonetheless, for the sake of the coming discussion, understanding treatments and enhancements as two separate categories of interventions should be adequate enough.

Once this has been posited, the question that then arises is how to understand health. Many accounts have been proposed in the philosophical literature on the topic. In what follows, we will follow Christopher Boorse’s influential view, which characterizes health as the absence of pathology, including disease and disability (Boorse 1997, followed by Daniels 2008).

5.2.2 Possible instances of the DiDIY use of cutting-edge research for enhancement purposes

We can think of three main categories of people who might potentially be interested in using DiDIY tools resulting from cutting-edge research for purposes of enhancement (as characterized in the previous subsection).

(1) The first such group is professional athletes. Various authors have suggested that as the relevant technologies improve, athletes might become increasingly interested in acquiring “enhanced” body parts – even if this meant replacing perfectly healthy ones – in their never-ending quest to gain a competitive edge over their competitors. The enhanced parts in question might include 3D printed prosthetic legs that allow an athlete to run faster than she could using her “natural” legs (Young 2015), or bioprinted body parts that mimicked natural ones yet featured stronger bones, or muscle tissue conducive to superior endurance or greater explosive power (Tran 2015). Presumably, the first type of enhancement could only be used – if at all – within disabled sports (which might then need to be re-named “enhanced sports”!), since sports governing bodies would be very unlikely to allow it within “regular” sport. The second type, by contrast, could conceivably infiltrate regular sport, since it might be much trickier to detect. For example, any visible surgical scars on the enhanced athlete might be justified by appeal to purported medical needs, and it is even conceivable that procedures might be developed that left no such scars.

As long as they were allowed by regulatory bodies, enhanced prosthetic limbs could in principle be manufactured by the athletes themselves using DiDIY tools. On the other hand, if enhancement through 3D bioprinting became the norm, it would likely occur in a hospital setting, and would not plausibly count as DiDIY. However, it seems quite possible that it might begin as a form of illegal performance enhancement, prohibited by sports governing bodies and pursued secretly by the athletes concerned, in which case they might be more likely to manufacture the enhanced parts in question using their own tools --ceven though they would still need the assistance of medical professionals to perform any surgical procedure –, and therefore to be engaging in DiDIY.

While the prospect of an athlete replacing a healthy body part with an enhanced one is philosophically fascinating, we note that it should nevertheless be viewed as mostly speculative at the present time, given the drastic, risky, and invasive procedures it would require (elective amputation of a healthy limb solely for enhancement purposes), which are likely to limit its appeal for the foreseeable future. That does not mean that it is completely outside the realm of possibility: healthy athletes could conceivably seek to join disabled sport in order to get access to enhanced prosthetic limbs, if for instance that category of sport had become more popular or prestigious than its “normal” counterpart, because it now led to more impressive athletic achievements thanks to the presence of such enhancements. Still, a more plausible type of case would involve an athlete who had lost a limb (or lacked one from birth) being fitted with a new one, whether prosthetic or biological, that not only replaced the original limb, but surpassed it in terms of its functionality (strength, endurance, etc). Cases of this type would seem to simultaneously count as both treatment and enhancement, and they could sometimes take the form of DiDIY (especially, in the case of 3D bioprinting, if the enhancement in question were against the rules of the sport).

(2) The second group is the military. The army would certainly have an interest in soldiers who were less susceptible to injury, could recover faster from it, and could carry out combat missions lasting for a longer period of time, and it might consider technologies like 3D printing and bioprinting to achieve those goals (Dodds 2015). For the reasons cited in relation to the previous point, however, we would again be dealing with a highly speculative scenario here if what we are discussing is the replacement of healthy body parts with enhanced ones. If such a procedure were to be carried out at all, it would most likely be done in a hospital context, not in a DiDIY manner. That said, here again there might be greater plausibility in a scenario involving soldiers who had lost a limb in war being fitted with a new, enhanced one, on the model of “battlefield DiDIY” described in subsection 5.1.

(3) The third group is made up of so-called “body hackers”, or “biohackers”, people who deliberately tinker with their own bodies, using modern technology, for artistic purposes, to improve their own capacities,[8] or sometimes just for the fun of it. Many are interested in becoming “cyborgs” of some kind (Wainwright 2015). The following two examples illustrate the nature of body hacking:

(a) Stelarc, an Australian performance artist, grew a human ear on his arm (see Figure 1) for the purpose of connecting it to the internet via a wifi-enabled device, which would also contain a microphone that would allow to broadcast the sounds from the environment around him online. The ear was grown from “an ear-shaped bio-polymer scaffold, inserted beneath his skin, which was then suctioned over the scaffold” (Wainwright 2015). As it happens, Stelarc does not appear to have engaged in DiDIY for the sake of that artistic experiment, but it is easy to imagine similar experiments that would involve DiDIY: for example, an artist could use her own personal 3D bioprinter to create the original scaffold, or even – at some point in the future – to print a full, bionic ear to be then grafted onto her arm (Lawrence 2016). There might be room for debate whether a procedure like the one undergone by Sterlarc counts as a true enhancement, or whether it is a different kind of bodily modification. Indeed, rather than *improving* an existing trait or capacity of the artist, Stelarc’s ear gives him a *new* ability, that of broadcasting the sounds that surround him on the internet. In the following discussion, we will adopt a broad understanding of enhancement that

8 In that respect, the competitive athletes we have previously described would represent one example of body hackers. For the sake of convenience, in what follows we will discuss these two categories of people separately.

treats the conferring of new abilities through technology as a form (perhaps a limiting case) of enhancement.

Figure 1 – Stelarc's "Ear on Arm" (http://www.gq.com/story/stelarc-third-ear-on-arm [accessed 18 December 2016]).

(b) Kevin Warwick, a former professor of cybernetics at the University of Reading, now Deputy Vice-Chancellor (Research) at Coventry University, has been experimenting with a variety of surgical implants as part of his so-called "Project Cyborg". In 2002, he thus had a 100-electrode chip implanted into the nerve fibres of his arm, which allowed him to control an electric wheelchair and an intelligent artificial hand, using signals transmitted from his wrist (Wainwright 2015). Though Warwick's case may not involve genuine DiDIY (the 2002 implantation procedure was carried out by medical professionals), others have followed in his footsteps, and they may potentially count as DiDIYers. One example is body hacker Tim Cannon, who is reported to have had a computer "the size of a small smartphone" implanted into his forearm, "without the aid of anaesthetic or a licensed doctor" (Whitwam 2013; see Figure 2). The computer, called the Circadia 1.0, is built on top of an Arduino microcontroller and is designed to gather biometric data and send them to a mobile device (*ibid.*). If someone like Cannon were to pursue the same research goals as Warwick, he may provide a full-fledged example of DiDIY in research.

Figure 2 – Tim Cannon's implant (http://www.geek.com/chips/man-implants-smartphone-sized-computer-in-arm-to-become-diy-cyborg-1575915 [accessed 18 December 2016]).

These are but two examples of the forms that body hacking can take today. The arrival of cutting-edge technologies like 3D bioprinting promises to give them many new avenues to explore. For example, they might be interested in using them to replace some of their own body parts in a manner analogous to the one we have previously described in relation to competitive athletes. In this context, we propose to distinguish between two different kinds of replacement of body parts: what we will call bodily *renewal* and bodily *augmentation*. To explain the first of these two notions, suppose that the process of replacing a failing organ with a new bioprinted one were perfected to the point where it could be done with reasonable reliability: the new organ would function roughly as well as a healthy organ can in the context of the body into which it has been transplanted (as well, say, as if we had used instead the "natural" organ of a healthy 20 year-old donor). One of the main therapeutic goals described in the previous subsection would have been achieved. But what if this process were repeated every time an organ failed, with no risk of rejection and no problem of scarcity? And what if, more generally, we could systematically replace defective human body parts (e.g., arteries, joints, muscles) with new 3D printed ones? If this could be done,[9] it seems that one might then be able to overcome several of today's leading causes of death, including heart and lung disease, thereby extending one's healthy lifespan by a number of years (Tran 2015, p. 158). Thus defined, bodily renewal seems to provide another counterexample to the dichotomy between treatments and enhancements, since it would both help maintain health, and allow elderly people to enjoy a higher level of energy and physical vigour than what is currently typical of even "healthy" people in old age.

Some, like Gabor Forgacs, founder of research company Organovo, have even suggested that bodily renewal might ultimately allow us to keep on living indefinitely, as some keep their classic cars going not only with proper maintenance but also by replacing failing parts when necessary (Kamen 2015). Such a suggestion, however, does not address the potential obstacle that there might be one body part we cannot replace, even in principle: arguably the most important organ of all, the human brain. True, partial brain transplants might in principle be feasible, and could help with certain types of harm to the brain such as strokes. 3D bioprinting could help produce the tissue required for such transplants: in fact, researchers at the University of Melbourne have already managed to print tiny spheres of brain tissue, thereby offering a proof of principle for this process (Rehman 2015). Still, it is questionable whether replacing an entire brain, assuming it ever became feasible, would be compatible with the preservation of the personal identity of the patient involved. And yet such complete replacement might ultimately be required, if only to counter the damages wrecked on the brain by the ageing process.

There is admittedly room for debate here, as such a process raises fascinating questions about personal identity: for instance, is the preservation of a person's original brain required for her survival, or is it enough to ensure that she is psychologically continuous with her former self (i.e., that she retains her initial memories, desires, or character traits)? And if the former is true, is it nevertheless in principle possible to preserve the original brain while *gradually* replacing each of its parts with new ones created via 3D bioprinting?[10] As we do not have the space to tackle such difficult questions here, and given the highly speculative nature of this "full brain replacement"

9 Admittedly, a number of technical challenges would have to be met for this to become possible. For instance, surgical procedures would have to be made safer than they are now, otherwise repeat surgeries would start posing a serious risk as one grew older.

10 An intuition that some people have in the so-called "Ship of Theseus" thought experiment, where all the parts of a ship are gradually replaced with new, qualitatively identical ones. For the application of this intuition to the case of the brain, see, e.g., Parfit 1984, p. 1034.

scenario, we will limit ourselves to concluding that while organ renewal thanks to 3D bioprinting may well hold an interesting potential for lifespan extension, it remains an open question whether this potential goes beyond a few years or decades at most, in the absence of interventions that would also stop or reverse the ageing process in the brain. Furthermore, the appeal of living to, say, 120 years old would be reduced if the last few decades of one's life were impaired by brain conditions like dementia, even if the rest of one's body were in good condition. Of course, it would be short-sighted to consider the potential impact of 3D bioprinting in complete isolation from other scientific breakthroughs, such as gene editing and stem cell therapies, which when combined could produce more spectacular results (Nordrum 2015). But it remains important not to treat it as a panacea to the radical extension of the healthy human lifespan.

By contrast with bodily renewal, bodily *augmentation* does not necessarily involve an iterated process of replacing body parts (though it can in principle do so). While it also involves the replacement of one's original organs and other body parts with new ones created via 3D bioprinting (or 3D printing, in the case of bionic limbs), these new parts will not just be fresh and well-functioning but also superior in efficiency and resilience to any human part produced the "natural" way (and they will sometimes be designed to perform entirely new functions, as we describe below). Furthermore, the parts that get replaced through that process need not be defective or deteriorating to any degree – they could in principle be in peak condition.

The scenario we have described above in which professional athletes replace healthy body parts with enhanced ones for the sake of gaining a competitive edge is one example of bodily augmentation. Uses of similar procedures for cosmetic purposes have also been suggested: an extreme, futuristic example imagined by Christopher Barnatt is that of a "face printer" that can "remove unwanted layers of flesh, bone and other tissue and replace them with new bioprinted cells according to the patient's specification" (Barnatt 2014) – though it is unclear to what extent such a futuristic procedure would be amenable to DiDIY. Interestingly, some have also suggested creating enhanced organs to ultimately serve medical purposes: one example that has been proposed is that of electricity-generating organs that could power electronic devices like pacemakers without the need for batteries (Neal 2014).

Body hackers are from the only people who might find bodily renewal and bodily augmentation appealing. Many members of the general public also would. Nonetheless, most people would presumably only consider undergoing such procedures if they were proposed in a hospital setting, in a fully professional form that left no room for DIY. Body hackers, on the other hand, might be more adventurous and seek to try them out while the relevant technologies were still being perfected, which might require them to manufacture their replacement parts themselves, on their own 3D printer. Given the risks associated with invasive surgical procedures, and the difficulty of persuading a qualified doctor to perform them outside of the traditional hospital context (since DIY surgery would seem like a rather unattractive idea), one-off forms of bodily augmentation might hold greater appeal for them than bodily renewal, which would require repeated surgeries. Furthermore, bodily augmentation might seem even more appealing, even among body hackers with their high tolerance of risk, in cases where someone has lost a limb and seeks to replace it with an upgraded one (combining, as we have said, therapy and enhancement). In any case, it is conceivable that the first successful cases of bodily augmentation (and perhaps even renewal) assisted by technologies like 3D printing will involve body hackers, and will qualify as DiDIY.

5.2.3 Possible instances of the DiDIY use of cutting-edge research for other non-therapeutic purposes

Besides the use of such forms of DiDIY for purposes of enhancement, other uses that fall outside that category have also been mentioned. For instance, the US army is reportedly about to experiment with 3D printed drones, which they could manufacture in 24 hours near the battlefield, in accordance with the latest needs of the moment (Atherton 2016). On a radically more speculative note, Tran (2015, p. 154) envisages a scenario worthy of a science-fiction novel in which people can make DiDIY copies of themselves:

> Imagine a future where an individual can simply bioprint another clone of herself at home; this is a scary yet exciting vision. Theoretically, cloneprinting would simply serve as a quick, easy modality of production. This comparison assumes that the future of bioprinting makes it possible to cloneprint a mammalian or human clone. Unlike bioprinting body parts, cloneprinting does not require doctors' assistance before the "products," i.e., clones, are ready for use. Similar to how bioprinting differs from synthetic biology, cloneprinting differs from cloning in that cloneprinting moves clone production out of the laboratory and into everyone's home, making cloneprinting more accessible than cloning.

While such a highly futuristic scenario, which was actually depicted in the 1996 movie *Multiplicity* with Michael Keaton, certainly raises many fascinating philosophical issues, it does seem somewhat too speculative to be worth discussing as anything more than a thought experiment at the present point in time.

5.2.4 Future timelines and the need to avoid confusion and hype

Perhaps it is not superfluous to emphasize again that our discussion in the past few subsections has been, to a significant extent, speculative in nature, since none of these applications of 3D bioprinting for purposes of enhancement exist in a workable form at the present time. Even when it comes to therapeutic applications, there is still much work to be done before 3D bioprinting can start fulfilling current hopes, despite the progress that has already been made in the field. Varkey and Atala thus write in 2015 that "we currently only have the technical capability to print microtissues; it will likely be a decade or more before we achieve the capability to commercially bioprint transplant size and compatible organs" (2015, p. 284). In order to avoid feeding a current of hype, as we have seen happen with other biomedical interventions such as so-called pharmacological "neuroenhancers", it is thus important to emphasize that the most promising applications of 3D bioprinting still lie in the future. Nevertheless, this may still be the relatively near future, since a decade or a few decades is not a huge amount of time. This is at least what experts are forecasting when it comes to treatment applications.

One might think that enhancement uses of 3D bioprinting will prove more challenging than therapeutic ones, and will therefore take much longer to get perfected. Ibrahim Ozbolat, the researcher who suggested the idea of electrogenic organs, thus estimates that such organs are "at least 100 years off" (Neal 2014). This particular futuristic case aside, however, it seems reasonable to assume that the time gap between the perfection of organ bioprinting for therapeutic and for enhancement purposes will not extend to that long a period of time, especially if we factor in the further advances that are likely to be made in connected fields such as gene editing and nanotechnology.

5.3 Ethical concerns with DiDIY uses of cutting-edge research

Both therapeutic and enhancement applications of such DiDIY practices raise ethical issues. Nevertheless, uses for enhancement purposes are still significantly more controversial than therapeutic ones. In what follows, we will take a survey of the ethical issues at stake.

5.3.1 Safety

Possibly the most important ethical concern has to do with the potential harm that such DiDIY procedures might cause, either to the users themselves or to others. This concern bears on both therapeutic and enhancement applications, although it probably has even greater salience with regards to the latter, given their less favourable risk-benefit ratio. Even when they are performed in a professional context, the interventions in question will call for rigorous quality control. When it comes to bioprinted tissues and organs for transplantation, for instance, Varkey and Atala mention in the American context that the Food and Drug Administration (FDA) "will evaluate all bioprinted tissues and organs for safety and effectiveness and assess the benefits and risks involved" (2015, p. 284). But quality control becomes even more of an issue in the context of DiDIY, where organizations like the FDA (and analogous Competent Authorities in EU countries) might not always be able to systematically monitor the quality of the organs that might get produced. Even if 3D bioprinters sold commercially were regulated as medical devices, which would offer some guarantee of quality regarding their output (despite, of course, the possibility of misuse), people would still be able to build DIY bioprinters that would not be subject to similar quality control (Flaherty 2013). And of course, surgical operations performed outside of the standard hospital context can pose serious safety issues. The danger of obtaining an organ from the black market is illustrated by the fact that buyers often catch hepatitis or HIV.

Concerns about risk would have even greater weight in cases where a DiDIYer were to create an experimental form of bioprinted material, say for enhancement purposes, rather than following an established protocol developed by professional scientists. By contrast, such concerns seem less salient when it comes to prosthetic devices as opposed to printed body parts, insofar as the former do not open the door to health complications in the same way (especially when no surgery is involved). It is also worth noting that enhancement uses of 3D bioprinting involve a range of more or less invasive procedures, and that the more invasive ones are likely to present a greater degree of risk. For instance, grafting new bioprinted skin onto someone is likely to present lesser risks than full-fledged organ replacement. Also, DiDIY bioprinting in institutional contexts such as the army might be subject to more stringent standards of quality control than DiDIY bioprinting by private individuals operating outside of such a context.

The question is then what the implications of all of this are at the regulatory level. One issue is whether it is ever permissible for medical professionals to assist with such DiDIY practices; we will discuss it in subsection 5.3.3. Beyond the issue of the proper role of doctors, a concern is that regulation of such practices could prove very challenging, if not impossible, in light of the context in which they might be taking place, such as the home of private individuals. In the case of the DiDIY manufacturing of organs for transplantation, it is fortunate that – for the reasons we mentioned – the likelihood of a black market flourishing does not seem high for the developed world. The developing world is a trickier case, especially as the procurement of organs from the black market, with all its attendant risks, is for a number of people the only alternative to certain death. Any effort to exert control over such a market should also ensure that it offers a better alternative to those people, and does not just deprive them of their only hope.

When it comes to enhancement applications, it seems that the case of competitive athletes, soldiers, and body hackers deserve different assessments. When it comes to the latter category, regulation would appear very challenging if not impossible in light of the context in which the relevant DiDIY practices would take place, such as the home of private individuals. To this technical difficulty, we should add the large degree of consensus in our society on the view that competent adults have the right to choose assume a certain level of risk to themselves, even for non-therapeutic purposes, as long as they do not harm others – which body hackers may be less likely to do than other groups like professional athletes or soldiers, for reasons we will discuss in a moment. In light of those considerations, together with the largely speculative nature of practices like the DiDIY bioprinting of entire body parts at the present time, it would seem inappropriate to advocate regulations seeking to ban or restrict self-experimentation by biohackers on their own bodies using the latest DiDIY tools. At the very most, we should emphasize the importance for any would-be biohackers to be properly informed about the risks presented by procedures that they are considering undergoing.

So far we have considered the risks that the use of cutting-edge DiDIY tools might pose to users. But could *users* that had enhanced themselves through DiDIY present a risk of harm to others, especially the unenhanced? This possibility is what prevents the conclusions we reached about body hackers from being simply extended to groups like professional athletes and soldiers. When it comes to the former group, athletes who used cutting-edge DiDIY to enhance their performance, in defiance of the rules of their sport, might be said to be behaving unfairly towards their rule-abiding competitors, and could also be creating coercive pressures on them to undergo similar interventions in order not to get left behind. These two pitfalls, which we shall address in subsections 5.3.4 and 5.3.2 respectively, suggest potential justifications for cracking down on such DiDIY performance enhancement. When it comes to the military, the issue of coercion is again relevant, insofar as soldiers might face a requirement to enhance themselves for the sake of performing their missions more effectively. Also, some authors have expressed worries about the creation of “super-soldiers” more resistant to injury, who might trigger a new type of arms race that would have harmful consequences for civilians; DiDIY could play a role in this process, which we will discuss in subsection 5.3.5.

Beyond issues of bodily modification, the ability to manufacture customized drugs at home also raises worries about safety. It opens up the prospect of DiDIY counterfeit drugs, or illegal drugs (whether old or new, experimental ones). How serious a threat to public health these represent is still unclear at this point: as mentioned in D3.3, we do not yet know how practical it will be to tinker with basic materials in order to create one’s own illegal DiDIY drugs, as opposed to using more traditional methods.

Finally, the worry has been raised that printable vaccines might be modified and turned into bio-weapons by rogue individuals or states (MacKenzie 2012). This is again an issue that falls within the province of D6.2.

5.3.2 Coercion

The concern that some people might get coerced to use enhancement technologies, once these become available, is a common one, and as we have just mentioned, it can be raised in relation to some forms of DiDIY as well. A major distinction usually drawn in this context is between *direct* and *indirect* coercion to enhance (Erler *forthcoming*). Direct coercion to enhance occurs when a source of authority puts forward, whether explicitly or implicitly, a requirement to use the relevant enhancement. An example of this involving 3D printing would be the army requiring soldiers who are to be sent on specific combat missions (whether based on conscription or because they volunteered for these) to have enhanced bioprinted parts, or 3D printed prosthetics, added to their bodies – and as we have said, these might sometimes get manufactured in a DiDIY manner, as the circumstances of war demanded. Such a requirement to enhance could be enforced in more or less harsh ways: at one extreme, a soldier who refused to undergo the enhancement could spend some time in prison for refusing to obey orders. But a more moderate and perhaps more likely punishment would simply be the inability for the soldier to participate in the missions in question, just as US pilots who refuse to take wakefulness-promoting agents like amphetamines or modafinil can be prevented from flying combat missions (Mehlman 2004). Of course, for soldiers who have been conscripted and would prefer not be sent on such missions, being sidelined would come as a blessing. But those who wanted to pursue a military career, especially one that involved missions of this kind, would likely see their plans thwarted if they resisted the enhancement.

In cases of indirect coercion, by contrast, no requirement to enhance is put forward by anybody. Rather, what happens is that, because a sufficient number of people in one's occupation start using enhancements, one finds oneself under increasing pressure to follow suit in order to remain competitive as a worker or job candidate. Competitive sports provide a context in which indirect coercion to enhance is already known to occur quite frequently. Especially in certain fields like cycling, we now know that athletes have long found themselves faced with the choice to either start using performance-enhancing drugs, even when such drugs are officially banned, or abandon any hope of competing at the highest level. Indirect coercion to enhance oneself using the latest DiDIY tools could be next.

How worried should we be about the prospect of soldiers and athletes becoming, respectively, directly and indirectly coerced to enhance themselves in such ways? Regarding the former case, using soldiers as guinea pigs for risky interventions does seem ethically unacceptable, unless it can be convincingly shown that the risk of harm to the soldier associated with the intervention is lower than the risk (s)he would face if (s)he were to embark on the planned mission without that enhancement (assuming the mission is not unreasonably risky to begin with). Furthermore, even when this can be shown, people's fundamental right to bodily integrity, which forbids any coercive intrusion into their body, might still make direct coercion to enhance objectionable. That said, while interventions that would require the replacement of healthy body parts would indeed infringe upon that right, others, such as fitting a disabled soldier with a prosthetic device that enhanced his performance, would not seem to do so. Direct coercion to enhance might therefore be acceptable in relation to the latter, less invasive type of intervention, at least in a context like the military (though the penalties for refusing such prospective enhancements should be commensurate with those inflicted for the refusal of using existing enhancements, such as stimulant drugs). Also, it might be argued that those who have entered the army out of free choice, rather than as a result of conscription, have thereby waived their right to bodily integrity, and that it is legitimate to directly coerce them to undergo certain invasive bodily modifications for enhancement purposes, provided that these have been shown to be reasonably safe and required for the effective completion of their missions (including ensuring the safety of their comrades-in-arms). This is a controversial ethical issue that would deserve further analysis.

Coming now to indirect coercion, some competitive athletes might be willing to take significant risks with their bodies and health for the sake of gaining a competitive edge. If such athletes were to rise to the top of their fields using the DiDIY methods we have described, other athletes would come under pressure to take similar risks, on pain of being left behind. Were this to happen, the need to protect those other athletes from such coercion would justify imposing a ban on the relevant interventions – or upholding such a ban, if one were already in place. That said, if the interventions in question could be shown to be sufficiently safe, one might conclude that the sheer existence of coercion to enhance, or an appeal to the right to bodily integrity, divorced from considerations of safety, would not be enough to warrant a ban. The reason would again be that pursuing a career in competitive sport is supposed to be a choice, not something that society imposes on anyone. In section 5.3.4, we will consider a different rationale for prohibiting this type of performance enhancement in sport.

5.3.3 Professional obligations of doctors

While some body hackers, such as Kevin Warwick, do make sure they get ethical approval for their self-experiments from hospital review boards, many do not. Instead, they either engage in DIY surgery, or embark on a long search until they finally find a doctor who is willing to perform the surgical procedures they request without ethical approval. It might be argued that doctors who choose to provide assistance in such cases are guilty of medical malpractice. On the other hand, one might wonder how harshly such doctors deserve to be judged, to the extent that by agreeing to these people's requests, they might – at least sometimes – prevent them from ending up severely harming themselves by attempting DIY surgery.

Moreover, even if one agrees that providing such medical services in the absence of ethical approval constitutes malpractice, and that doctors have no duty to provide such services to people with no demonstrable medical need, it is still possible to ask whether ethical approval *should* be granted more liberally than it is now to requests from body hackers, so that doctors would at least be *permitted* to assist with such requests if they wish to do so. How exactly should the biohackers' right to do what they want with their bodies be balanced against the doctors' professional duty to do no harm to their patients? Questions like these will likely become increasingly relevant over the next few years, as body hackers keep thinking of new ways of tinkering with their own bodies using the latest technologies.

5.3.4 Justice/fairness

We have seen that one reason why athletes that illegally enhanced their performance using DiDIY tools might be acting wrongly would be that they might indirectly be putting pressure on other athletes to do risky things to their own bodies in order to keep up. Another reason might be that the former athletes would be behaving unfairly towards their competitors by using enhancements that were not allowed by the rules: they would be guilty of cheating. One possible response to this, which reflects current practices in professional sports, is to impose penalties on those who engage in such behaviour. We have also seen, however, that some of these DiDIY practices (especially those involving 3D bioprinting, which could convincingly mimic natural human tissue) might be challenging to detect, making such penalties difficult to enforce. On that basis, some would argue that a better solution would simply be to change the rules so as to allow the offending enhancements, provided that these could be shown to be safe enough (Savulescu et al. 2004).

Others might appeal to considerations of fairness to counter that proposal: even safe enhancements should be banned from competitive sport, they might argue, because they confer an unfair competitive advantage on those who use them. This line of argument might have some force in a hypothetical scenario in which the DiDIY tools required to get the relevant enhancements were only available to a chosen few with the right amount of wealth or connections. However, it becomes less convincing if we assume that the relevant tools could in principle be widely used, if only sports governing bodies chose to allow them. While some athletes might then still be unwilling to use them, and suffer a competitive disadvantage as a result, it would not seem to convincing to argue that they had been treated unfairly if they abstained from enhancement out of pure personal preference (rather than, say, because they could not afford it, or could expect it to harm their health).

5.3.5 The risk of an enhancement arms race

We have already briefly alluded to the worry that using cutting-edge technology, including in its DiDIY applications, to enhance the resistance of soldiers to injury in armed combat might lead to the development of even more dangerous weapons to overcome this enhanced resistance, thereby increasing the harm to which civilians are exposed (Dodds 2015). Is the risk of triggering an enhancement arms race a significant concern that might call for the imposition of some restrictions on the development of those technologies, or at least on their implementation in the military context?

Given the current evolution of technology, one might wonder whether autonomous weapons, including umanned aerial vehicles (UAVs) or drones, are not likely to have a greater impact on the future of war than “super-soldiers”, which armies around the world will presumably try to avoid using whenever machines can do the job instead (which should become more and more frequent). Furthermore, one might argue that if it becomes relatively easy to create new body parts for people, the risk of harm in war for both civilians and soldiers will be reduced. Once the relevant procedures had been perfected in the military context, they would likely soon lead to civilian applications (assuming these were not already available). Of course, as we have mentioned previously, ethical oversight should be exercised to protect soldiers from becoming guinea pigs for unsafe interventions.

Against the prospect of these technologies trickling down from soldiers to civilians, one might object that enhanced bioprinted body parts would be unlikely to be equally available to all. At least for some time, it might remain the prerogative of the military. Furthermore, the most technologically advanced armies of the world would gain access to the technology before their rivals, furthering inequality between them on the battlefield (which to some degree takes us back to concerns about fairness). The first point is mostly conjectural and may prove incorrect. Even if it is correct, moreover, it is not clear that it must necessarily result in greater harm to civilians. It might depend on who gains access to the technology; one could imagine that it might actually help shorten wars and reduce the number of casualties (as well as reducing the number of lifelong disabilities among veterans). As to the second point, it may well be correct, yet it would not make the military application of the relevant technologies (and DiDIY tools) any different from the application of technology in war more generally. Fears about wars getting bloodier and more destructive should probably concentrate chiefly on new forms of weaponry, such as biological and nuclear weapons and autonomous weapons systems – not on technologies like 3D bioprinting, which will mostly play the role of preventing death and injury, and could in this regard play a mostly positive role.

5.4 Conclusions on DiDIY and research

Combining the discussions in sections 4 and 5 of this deliverable, we get the following conclusions regarding the ethical issues surrounding DiDIY and research (a topic that includes both DiDIY *in* research, and DiDIY applications of cutting-edge research).

- The introduction of DiDIY in the research context allows both professional and amateur scientists to have access to the equipment they need at a much lower cost, thereby broadening participation in scientific research and facilitating the pursuit of audacious research projects that might otherwise have struggled to find support.

- Ethical issues pertaining to citizen science can also arise in a DiDIY context, but the practice of DiDIY by itself does not contribute to raising such issues.
- Products of cutting-edge research such as 3D bioprinters can be used as DiDIY tools for both therapeutic purposes (organ transplantation, home printing of customized drugs) and non-therapeutic ones, in particular human enhancement.
- Professional athletes, soldiers, and biohackers are three major examples of social groups that are likely to take an interest in the use of such DiDIY tools for enhancement purposes.
- The main concern raised by both therapeutic and enhancement uses of the relevant tools is safety. If our concern is to protect people from the harm they might inflict on themselves, the solution mostly seems to be to educate them about the possible consequences of the interventions they wish to undergo, so they can make informed decisions. If we are concerned about the harm they might cause to others, trying to enforce a prohibition on certain interventions might be justified in contexts like competitive sport.
- Concerns about coercion are relevant, especially when it comes to enhancement, but it is not clear that they have genuine force independently of other, intermingled factors such as safety (at least if the coercion one is facing is contingent upon the choice one has made to pursue a particular career).
- Further reflection is desirable regarding the exact implications of doctors' professional duties when it comes to dealing with requests for medical services (e.g., surgery) from people, like body hackers, who are not guided by genuine medical needs.
- A prohibition on the use of DiDIY tools for enhancement purposes is supported by certain ethical considerations, but only in specific contexts and under specific sets of assumptions. No general presumption against such use seems defensible, in light of both the various potential benefits of the use of those tools (even for enhancement purposes), and of the importance of respecting individual autonomy as long as it does not encroach on the rights of others.

References

ANONYMOUS. 2006. Psst, Wanna Buy a Kidney? *The Economist*: http://www.economist.com/node/8173039?story_id=8173039 [Accessed 19/12/2016].

ANONYMOUS. 2015a. 3D Printing Helps Plastic Surgeon to Perform Groundbreaking Scar-Free Facial Reconstruction. http://www.3ders.org: http://www.3ders.org/articles/20151113-3d-printing-helps-plastic-surgeon-perform-first-scar-free-facial-reconstruction.html [Accessed 19/12/2016].

ANONYMOUS. 2015b. Explore the British Museum and 3D Print its Artifacts All from the Comfort of Home (http://www.3ders.org): http://www.3ders.org/articles/20151224-explore-the-british-museum-and-3d-print-its-artifacts-all-from-the-comfort-of-home.html [Accessed 9/7/2016].

ANONYMOUS. 2016a. How 3D Printed Pills Are Personalizing Medicine (http://www.3ders.org): http://www.3ders.org/articles/20160102-how-3d-printed-pills-are-personalizing-medicine.html [Accessed 17/12/2016].

ANONYMOUS. 23 June 2016b. The Printpocalypse: A Threat to Civilisation? *thefullapple*: http://thefullapple.com/2016/06/23/the-ethical-debate-surrounding-3d-printers-the-printpocalypse-a-threat-to-civilisation.

ATHERTON, K. D. 2016. A Drone Today for a Battle Tomorrow. *Popular Science*: http://www.popsci.com/army-wants-to-3d-print-drones-in-24-hours [Accessed 19/12/2016].

BARNATT, C. 2014. *3D Printing: Second Edition*, CreateSpace Independent Publishing Platform.

BARNETT, R. C. & SABATTINI, L. 2009. A History of Structural Barriers to Women in Science: from Stone Walls to Invisible Walls. *In:* SOMMERS, C. H. (ed.) *The Science on Women in Science.* Washington, D.C.: The AEI Press, 54-78.

BOORSE, C. 1997. A Rebuttal on Health. *In:* HUMBER, J. M. & ALMEDER, R. F. (eds.) *What Is Disease?* Totowa, N.J.: Humana Press.

BUSCH-VISHNIAC, I. J. & JAROSZ, J. P. 2007. Achieveing Greater Diversity Through Curricular Change. *In:* BURKE, R. J. & MATTIS, M. C. (eds.) *Women and Minorities in Science, Technology, Engineering and Mathematics: Upping the Numbers.* Cheltenham, UK; Northampton, MA, USA: Edward Elgar, 245-75.

CAIN, S. 2012. *Quiet : the Power of Introverts in a World that Can't Stop Talking*, London, Viking.

CAMPBELL, M. 2011. 3D Printing: Build your Crazy Robot Ideas at Home. *New Scientist*: http://www.newscientist.com/article/mg21128235-900-3d-printing-build-your-crazy-robot-ideas-at-home [Accessed 14/12/2016].

CAPRILE, M., PALMEN, R., SANZ, P. & DENTE, G. 2015. Encouraging STEM Studies for the Labour Market. European Parliament.

CECI, S. J. & WILLIAMS, W. M. 2007. Are We Moving Closer and Closer Apart? Shared Evidence Leads to Conflicting Views. *In:* CECI, S. J. & WILLIAMS, W. M. (eds.) *Why Aren't More Women in Science? Top Researchers Debate the Evidence.* Washington, D.C.: American Psychological Association, 213-36.

CHALABI, M. 2013. The Pisa Methodology: Do its Education Claims Stack Up?. *The Guardian*: http://www.theguardian.com/news/2013/dec/03/pisa-methodology-education-oecd-student-performance [Accessed 25/7/2016].

DELOITTE CENTER FOR THE EDGE & MAKER MEDIA 2014. Impact of the Maker Movement. Deloitte Center for the Edge, Maker Media.

DODDS, S. 2015. 3D printing raises ethical issues in medicine. *ABC Science*: http://www.abc.net.au/science/articles/2015/02/11/4161675.htm [Accessed 9/4/16].

DOUGHERTY, D. 2012. Learning by Making: American Kids Should Be Building Rockets and Robots, Not Taking Standardized Tests. *Slate*: http://www.slate.com/articles/technology/future_tense/2012/06/maker_faire_and_science_education_american_kids_should_be_building_rockets_and_robots_not_taking_standardized_tests_.html [Accessed 24/6/2016].

DVORSKY, G. 2014. Are The Threats From Synthetic Bioweapons Being Exaggerated? *io9*: http://io9.gizmodo.com/are-the-threats-from-synthetic-bioweapons-being-exagger-1636829313 [Accessed 16/12/2016].

ERLER, A. 2016. A Prioritarian Critique of the Treatment-Enhancement Distinction. *13th World Congress of Bioethics.* Edinburgh.

ERLER, A. Forthcoming. Neuroenhancement, Coercion, and Neo-Luddism. *In:* VINCENT, N. A. (ed.) *Neuro-Interventions and the Law.* Oxford: Oxford University Press.

FICHTNER, A. Year Missing. Biohacking: More Human than Human. *Hacker Chick* [Online]. Available from: https://hackerchick.com/biohacking-more-human-than-human/ 2016].

FLAHERTY, J. 2013. Wannabe Scientists Build Structures from Living Cells. *Wired*: http://www.wired.com/2013/01/diy-bio-printer [Accessed 19/12/2016].

FLEMING, L. & KRAKOWER, B. 2016. Makerspaces and Equal Access to Learning. *Edutopia*: http://www.edutopia.org/blog/makerspaces-equal-access-to-learning-laura-fleming-billy-krakower [Accessed 1/8/2016].

GODSEY, M. 2015. When Schools Overlook Introverts. *The Atlantic*: http://www.theatlantic.com/education/archive/2015/09/introverts-at-school-overlook/407467 [Accessed 5/7/2016].

GREEN, F., MACHIN, S., MURPHY, R. & ZHU, Y. 2010. The Changing Economic Advantage From Private School. London: London School of Economics.

GRIFFITHS, A. 2014. 'DIY Labs Offer an Agile Alternative to University-Based Research'. *The Guardian*: http://www.theguardian.com/higher-education-network/blog/2014/jun/16/diy-labs-exciting-alternative-university-science-research [Accessed 15/10/2016].

GROSS, D., PIETRI, E. S., ANDERSON, G., MOYANO-CAMIHORT, K. & GRAHAM, M. J. 2015. Increased Preclass Preparation Underlies Student Outcome Improvement in the Flipped Classroom. *CBE-Life Sciences Education*, 14**,** ar36.

HATCH, M. 2013. *The Maker Movement Manifesto : Rules for Innovation in the New World of Crafters, Hackers, and Tinkerers*, New York, McGraw-Hill Education.

HENSELER, C. & RIEFFEL, J. 2014. The Maker Movement and the Humanities: Giving Students A Larger Toolbox. *The Huffington Post*: http://www.huffingtonpost.com/christine-henseler/the-maker-movement-and-th_b_6349514.html [Accessed 3/8/2016].

HORN, M. B. 2014. MOOCs for High School: Unlocking Opportunities or Substandard Learning? *Education Next*, 14: http://educationnext.org/moocs-high-school [Accessed 12/7/2016].

JUENGST, E. T. 1998. What Does Enhancement Mean? *In:* PARENS, E. (ed.) *Enhancing Human Traits: Ethical and Social Implications.* Washington, DC: Georgetown University Press, 29-47.

KAMEN, M. 2015. Bioprinting human tissue may yield cruelty-free drugs, and immortality. *Wired*: http://www.wired.co.uk/news/archive/2015-10/16/gabor-forgacs-wired-2015 [Accessed 9/4/16].

KELLOGG, S. 2012. The Rise of DIY Scientists: Is It Time for Regulation? *DC Bar*: http://www.dcbar.org/bar-resources/publications/washington-lawyer/articles/may-2012-diy-scientist.cfm [Accessed 14/12/2016].

KRASSENSTEIN, E. 2014. Why 3D Printing Needs to Take Off in Schools Around the World. *3DPrint.com*: https://3dprint.com/27743/3d-printing-benefits-schools [Accessed 9/7/2016].

KRAUT, R. 2016. Aristotle's Ethics. *In:* ZALTA, E. N. (ed.) *The Stanford Encyclopedia of Philosophy.* Spring 2016 Edition ed.

KRUEGER, N. 23 December 2014. 9 Resources for Teaching Digital Citizenship. *ISTE Connects Blog*: //http://www.iste.org/explore/articleDetail?articleid=242.

LANE, E. 2014. As Do-It-Yourself Manufacturing Emerges, Experts Consider Security Risks. *AAAS*: http://www.aaas.org/news/do-it-yourself-manufacturing-emerges-experts-consider-security-risks [Accessed 17/12/2016].

LAWRENCE, E. 2016. Medical 3D-Printing: Lives Being 'Remade' to Order. *The Courier Mail*: http://www.couriermail.com.au/news/queensland/medical-3dprinting-lives-being-remade-to-order/news-story/72e711d4374511510de915f55710afb7 [Accessed 18/12/2016].

LEVY, J. & KIMURA, D. 2009. Women, Men, and the Sciences. *In:* SOMMERS, C. H. (ed.) *The Science on Women in Science.* Washington, D.C.: The AEI Press, 202-84.

MACKENZIE, D. 2012. Craig Venter's Plan to Email Vaccines Around the World. *New Scientist*: http://www.newscientist.com/blogs/shortsharpscience/2012/10/craig-venter-email-vaccine.html.

MAHONEY, J. 2013. Better Education Can Combat Cyber-Bullying, Not Legislation, Expert Says. *The Globe and Mail*: http://www.theglobeandmail.com/news/national/increase-education-of-cyber-bullying-not-legislation-expert-says/article14551314/ [Accessed 2/8/2016].

MARTINEZ, S. L. & STAGER, G. S. 2015. Making Matters! How the Maker Movement Is Transforming Education. *We Are Teachers*: http://www.weareteachers.com/blogs/post/2015/04/03/how-the-maker-movement-is-transforming-education [Accessed 9/7/2016].

MEHLMAN, M. J. 2004. Cognition-Enhancing Drugs. *Milbank Quarterly*, 82**,** 483-506.

NATIONAL RESEARCH COUNCIL, NATIONAL ACADEMY OF ENGINEERING & COMMITTEE ON INTEGRATED STEM EDUCATION 2014. STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research. Washington, D.C.: The National Academies Press.

NEAL, M. 2014. 3D Bioprinters Could Make Enhanced, Electricity-Generating 'Superorgans'. *Motherboard*: http://motherboard.vice.com/read/3d-bioprinters-could-make-enhanced-electricity-generating-superorgans [Accessed 9/4/16].

NORDRUM, A. 2015. How To Live Longer: Scientists Are Pushing To Make 120 The New 70. *International Business Times*: http://www.ibtimes.com/how-live-longer-scientists-are-pushing-make-120-new-70-1900609 [Accessed 10/5/2016].

O'DONNELL, K. 2015. The Teaching Tax: How Inequality in Education Persists. *Harvard Political Review*: http://harvardpolitics.com/special_features/school-funding.html [Accessed 26/11/2016].

OECD 2015. Students, Computers and Learning: Making the Connection. *PISA.* Paris.

PARFIT, D. 1984. *Reasons and Persons,* Oxford, Clarendon Press.

REHMAN, A. 2015. Melbourne Researchers 3D Print Brain Tissue. *3D Print Headquarters*: http://3dprinthq.com/melbourne-researchers-3d-print-brain-tissue [Accessed 30/4/16].

RESNIK, D. B., ELLIOTT, K. C. & MILLER, A. K. 2015. A Framework for Addressing Ethical Issues in Citizen Science. *Environmental Science & Policy,* 54**,** 475-81.

SAVULESCU, J., FODDY, B. & CLAYTON, M. 2004. Why we should allow performance enhancing drugs in sport. *British Journal of Sports Medicine,* 38**,** 666-670.

SOMMERS, C. H. 2009. Sex, Science, and the Economy. *In:* SOMMERS, C. H. (ed.) *The Science on Women in Science.* Washington, D.C.: The AEI Press, 79-103.

SPELKE, E. S. & GRACE, A. D. 2007. Sex, Math and Science. *In:* CECI, S. J. & WILLIAMS, W. M. (eds.) *Why Aren't More Women in Science? Top Researchers Debate the Evidence.* Washington, D.C.: American Psychological Association, 57-77.

TRAN, J. L. 2015. To Bioprint or Not to Bioprint. *North Carolina Journal of Law and Technology,* 17**,** 123-78.

VANDEWEYER, M. 6 May 2016. The Growing Need for Developing (the Right) STEM Skills. *OECD Skills and Work*: https://oecdskillsandwork.wordpress.com/2016/05/06/the-growing-need-for-developing-the-right-stem-skills/comment-page-1.

VARKEY, M. & ATALA, A. 2015. Organ Bioprinting: a Closer Look at Ethics and Policies. *Wake Forest Journal of Law & Policy,* 5**,** 275-98.

WAINWRIGHT, O. 2015. Body-Hackers: the People Who Turn Themselves into Cyborgs. *The Guardian*: http://www.theguardian.com/artanddesign/architecture-design-blog/2015/aug/14/body-hackers-the-people-who-turn-themselves-into-cyborgs [Accessed 26/6/2016].

WEBB, M. & DOMAN, E. 2016. Does the Flipped Classroom Lead to Increased Gains on Learning Outcomes in ESL/EFL Contexts? *The CATESOL Journal,* 39**,** 39-67.

WHITWAM, R. 2013. Man Implants Smartphone-Sized Computer in Arm to Become DIY Cyborg. *Geek*: http://www.geek.com/chips/man-implants-smartphone-sized-computer-in-arm-to-become-diy-cyborg-1575915/ [Accessed 18/12/2016].

WOLF, L. K. 2013. 3-D Printers Move Into Research Labs. *c&en,* 91: http://cen.acs.org/articles/91/i7/3-D-Printers-Move-Research.html [Accessed 14/12/2016].

WORDSWORTH, R. 2016. Could 3D-Printed Organs Be Medicine's Next Grisly Black Market? *Wired*: http://www.wired.co.uk/article/printed-organs-black-market [Accessed 20/12/2016].

WORLD ECONOMIC FORUM 2016. The Future of Jobs: Employment, Skills and Workforce Strategy for the Fourth Industrial Revolution. Geneva, Switzerland: World Economic Forum.

YOUNG, M. 2015. Printing 3D Prosthetics for Athletes: Now Everyone Can Play. *Sport Techie*: http://www.sporttechie.com/2015/12/15/technology/printing-3d-prosthetics-athletes-now-everyone-can-play [Accessed 18/12/2016].