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Impact of a mixed-media digital CDM tool on new graduates' ability to spot construction hazards

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Abstract

Research has shown that up to half of construction accidents in the UK had a connection to the design. The UK's Construction (Design and Management) Regulations (2015) place duties on designers of construction projects to consider the health and safety implications of their designs. However, the majority of designers fail to recognise the impact on health and safety that they can make. Previous work shows that visual methods have been used to develop shared mental models of construction safety and health hazards in construction and design teams. There could also be links to alternative construction processes that may be utilized by the designer to reduce the inherent hazards in the design, thereby enhancing their knowledge of construction and maintenance processes from the very people who are affected by the designs.

The study reported in this paper aimed to improve how designers involved in construction projects learn about how their design influences the management of occupational health and safety once the design is implemented. The method involved the development of a multi-media digital tool for educating designers on typical design-related hazards. This tool was used in an intervention study with novice (n:20) and experienced (n:20) designers, split evenly between experimental and control groups. These groups were assessed via a novel hazard test using fictitious CAD drawings.

The results showed all experimental groups outperformed control groups, with the novice groups demonstrating the greatest increase in both hazards spotted and quality of alternative options recommended. Current research in this area promotes automated design choices for designers via Building Information Modelling (BIM). However, the research presented here advocates keeping the 'human' in control, supplementing designers' knowledge with tacit knowledge gained from interaction from the developed digital tool, so that they can make informed decisions.

Keywords: CDM, Design, Prevention through Design, Safety in Design

1. Introduction

Several research teams have investigated the relationship between design and construction accidents with Haslam et al. reporting that up to half of the accidents that they analysed had a connection to the design (Haslam, 2005). The UK's Construction (Design and Management) Regulations (2015) place duties on designers of construction projects to (amongst other things) consider the health and safety implications of their designs in relation to the construction, use and maintenance (including cleaning) of the structures produced. However, the majority of designers fail to recognise the impact on health and safety that they can make (Haslam, 2005). Several reasons have been identified as being barriers; lack of resources and time, cost, client requirements and a lack of tacit knowledge gained through experience (Haslam, 2005; Behm, 2005). This last factor was explored by Hayne et al. who showed a link between site experience and the designer's ability to identify and mitigate construction hazards in designs (Hayne G., 2015).

Unfortunately, designers of construction in the UK are increasingly educated and trained with little or no site experience (Hayne G., 2015). Specifically, the main design professional institutions have been gradually withdrawing the requirement for architects and engineers to spend prolonged periods of time resident on construction sites. The situation is compounded by the increased academic requirement of a master's degree in order to become chartered by the conventional route and the tendency of universities to produce "engineering scientists" (Hayne G., 2015). Designers are increasingly working purely within the design office environment. They are immersed in the use of digital technologies, working in isolation, and not challenging the outputs of their computers. Essentially, they are becoming over-reliant on computer-generated information, which is eroding their skills, knowledge and experience of imperatives critical to health and safety (Hayne G., 2015). It is therefore important that the details of potential hazards are communicated to designers in a way that will aid their development and training, augmenting the site experience they have (if any). This can be achieved by the use of links to visual files demonstrating the construction and maintenance process complete with experiences of construction operatives, foremen and facilities managers etc. to explain the actual details of the hazards.

The study reported in this paper aimed to improve how designers involved in construction projects learn about how their design influences the management of occupational health and safety once the design is implemented. Previous work shows that visual methods have been used to develop shared mental models of construction safety and health hazards in construction and design teams (Hare, 2013) (Lingard, 2015; Zhang, 2015). There could also be links to alternative construction processes that may be utilised by the designer to reduce the inherent hazards in the design, thereby enhancing their knowledge of construction and maintenance processes from the very people who are affected by the designs. Current research in this area promotes automated design choices for designers via Building Information Modelling (BIM) (Liu, 2014; Zhang, 2013). However, the research study presented here advocates keeping the 'human' in control, supplementing designers' knowledge with experiential knowledge, so that they can make informed decisions.

1.1 Design for Occupational Safety & Health (DfOSH)

There have been a number of studies undertaken in recent years, using terms such as 'Design for Safety' (DfS), 'Prevention through Design' (PtD), 'Safety in Design' (SiD) and 'Design for Health' (D4H). These terms seem to be used interchangeably and can be collectively referred to as 'Design for OSH' (DfOSH). Therefore, this is the term adopted for the study reported here, even though these other terms may have been used by the authors cited.

Trethewy and Atkinson (Trethewy & Atkinson, 2003) define the principle of DfOSH as "Improved safety, health and environment outcomes through better design...". In order for this process to be effective, hazards need to be identified during the design process and where possible eliminated or minimised (Behm, 2005; Toole & Gambatese, 2008; Trethewy & Atkinson, 2003). It is acknowledged

that accident causation is often complex and multi-faceted (Gibb, 2006; Martínez Aires, 2010; Gambatese, 2008). However, research has been undertaken within the UK that shows that up to half the accidents having a link to design whilst accepting it is often not the sole cause and other factors also contribute (Haslam, 2005). This figure is close to that noted in the European Union directive 92/57/EEC (EU-OSHA) 13 years earlier and after the introduction of the CDM Regulations.

The results of the research by Haslam (2005) align with the comments in the European Union Directive 92/57/EEC and further suggest that little improvement had been made in the decade following the introduction of the Construction (Design and Management) Regulations (1994). It is important to recognise that this comment relates specifically to statistics and ignores the heightened awareness noted by Howarth et al (2000). Considering such comments, it is reasonable to assume that many UK designers fail to appreciate the benefits of DfOSH. Researchers have found that many designers do not recognise the impact on OSH that they, as designers, can make (Haslam, 2005). Gambatese and Hince (1999) undertook a study in the USA where they identified that designers are not aware of their impact on site safety and lack the knowledge and ability to modify their designs to improve safety. This view is also supported by the work carried out by Qi et al. (2011). It should be noted that unlike the UK, American designers do not have a legal, contractual or regulatory requirement to consider OSH within their designs (Behm, 2005).

Few UK designers embrace the principle of DfOSH despite the CDM regulations being in force (Haslam, 2005). Several reasons have been identified as barriers to designers; lack of resources and time, cost, client requirements and a lack of tacit knowledge gained through experience (Haslam, 2005; Behm, 2005). Other research teams have also highlighted that designers are reliant upon tacit knowledge (Morrow, 2015; Gangolells, 2010; Hadikusumo, 2004).

As a design is a representation or simulation of the complete artefact it must be questioned how a designer undertakes the process of DfOSH. It has already been suggested that designers are reliant upon tacit knowledge, often developed from experience. The additional factor that is required is the ability to imagine, which Bronowski (1979) clearly links with vision. Bronowski goes on to suggest that humans are unique in that they can imagine and consider options which in the case of DfOSH would include construction processes previously witnessed, that would allow the adoption of processes with the least hazards. Foresight is also required when a design is reviewed, experience should give foresight of the consequences of the design and the associated construction process that has been imagined. Again Bronowski (1979) suggests that foresight is unique to the human but has been evident for millennium. He provides the example of the discovery of stones in Olduvai that were stockpiled for use as stone tools. Ancient man had the experience that his stone tools would break and need replacing, hence he would collect suitable stones for later use. Subsequent research has identified that other animals such as primates possess the ability to imagine (Suddendorf, 2006) but this does not detract for the need for imagination when undertaking DfOSH. Designers need foresight to anticipate what may occur when operators are constructing and maintaining their designs. For example, foresight will tell a designer that mechanical plant on the roof will need servicing and a safe access route to the plant will be required that will not put the maintenance staff at risk. This is a simple example that most designers would hopefully be aware of but a more complex hazard could be that the plant will need replacing. Has the design allowed for a crane of suitable size to be located close to the plant or does the landscaping, with its planting and water features, prevent the use of a crane? If the designer has not been exposed to the latter situation their experiences will not give them the foresight to anticipate the situation arising.

The HSE have produced 'red, amber, green lists' (RAG lists) that are described as practical aids for designers, highlighting what to avoid and what should be encouraged (CITB, 2015). The guides are often referred to during training sessions on CDM and designing for OSH as they are brief and simple to use. Curiously, the majority of the recommendations relate to the detailed design stage of a project when the opportunity to achieve maximum impact has already passed. This could provide assistance to inexperienced designers who may not consider DfOSH during the design, but not as useful for earlier stages (Morrow 2015). Inexperienced designers may also use the RAG lists as a check list without looking for additional hazards (Hayne, 2016).

Notwithstanding the above discussions pertaining to the impact that design decisions have on the causation of accidents, it is important to remember that “It is incorrect to assume that simply by implementing the design for safety concept, construction site fatalities will automatically be eliminated” (Gambatese, 2008). Whilst many attempts have been made to develop digital tools to aid designers in this respect, including those embedded within BIM technology, the need for the designer to be competent is a common thread. The nature and scope of education for designers, combined with relevant site experience, has shown to be critical to successful DfOSH outcomes. Therefore, technology that seeks to remove the designer from the decision making process around DfOSH – such as automated processes – could do more harm than good. A knowledge based system seems to be the favoured method of giving designers the ability to make informed decisions on DfOSH. However, text-based systems have proven to be cumbersome. Whereas, visual (pictorial, multimedia) databases may be able to overcome the problems posed by overly word-based systems and provide a more effective solution. It is acknowledged that designer knowledge is only one of many factors that can influence DfOSH (e.g. available budget, competing objectives, form of procurement, etc.) however, these are outside the scope of this paper.

2. Research methods

The method employed was one of exploratory action research, combined with the use of an experimental design to evaluate the ability of a multimedia digital tool intervention on designers’ OSH knowledge and practices. This was expected to improve how designers can influence specific hazards (relating to construction, use and maintenance of structures). To achieve this, the following methods were employed:

Sector-specific hazards, which can be influenced by designers of buildings and structures, were identified through a systematic review of academic and industry literature. The literature search was supplemented by interviewing experienced Health and Safety Executive (HSE) Construction Division inspectors, construction OSH professionals and facilities managers. Other experienced professionals were recruited from the research team’s industry network. This included Directors or Senior Managers.

The ‘design influenced hazards’ informed the development of a multi-media digital tool (Figure 1) and linked hazard test instruments in the form of Computer Aided Design (CAD) drawings. The new BIM PAS 1192-6 (2018) for OSH information was used as the main reference point. A consequence of this was to specifically label designer-related hazards in relation to the three ‘attributes’ of ‘Product’; ‘Activity’; and ‘Location’. Therefore, each hazard in the database could be labelled in relation to one or more of these attributes, e.g.:

- Products: such as substances, materials, components and elements);
- Activities: such as working at height; and
- Locations: such as a confined crawl space.

Another critical step in classifying hazards in the database was to include the type(s) of injuries or harm resulting from each hazard. Again, the classifications in the new BIM PAS 1192-6 (2018) were utilised e.g. ‘fall from ladder’ ‘electric shock’ etc. The digital tool was developed iteratively, with pilot testing and refinement until it was deemed ready for the experiment.

A sample of 40 designers (based on the timeframe for the study), from two typical industry groups of architects and civil engineers, were recruited for the next stage of the research. These were recruited via the network of designers who have attended CDM courses and the network of designers known to the research team. The sample was purposefully chosen using the following criteria; half (20) experienced (deemed as more than 5 years’ experience, which must include site experience) and half (20) novice (less than two years post graduate).

Designers were invited to engage with the developed materials in a carefully controlled experiment. The experiment evaluated the effects of the multimedia materials on decision-making and users' capability in designing for OSH in the construction industry. The experiment determined whether use of the multimedia materials improved users' ability to foresee OSH hazards in designs by measuring both the quantity of specific hazards identified and the quality of design outcomes (design controls) put forward.

The sample of 20 novice and 20 experienced design professionals were randomly assigned into multimedia user (experimental) and non-user (control) groups. Design problem scenarios were presented to participants in sessions in a controlled environment. Participants were asked to review the set of CAD drawings in these sessions, to identify hazards and make decisions about designing for OSH. An explanation was given to the participants of what was expected and they were given an opportunity to ask any questions. For the first part of the experiment, all participants were asked to use their own knowledge to identify hazards and alternative solutions. In the second part of the experiment, participants were split into two groups: those who used the tool to identify hazards and alternatives and those who used their own resources, for example: the HSE website. Participants were allowed to use the second half of the experiment to not only add new hazards and alternatives but to also edit their current ones if they wanted. The pre-intervention responses were written with a red pen and the post-intervention responses with a green pen to distinguish between both.

The average (mean) number of project-specific hazards identified per group was measured. Following the method used by Hayne et al (2015), generic hazards were ignored. Out of scope items included general references to e.g. work at height (if not related to a project-specific item); general good practice to comply with Building Control/Standards, such as fire protection; or those considered out of scope for not being OSH related. The hierarchy of controls score (from 5 down to 1) also followed the Hayne et al (2015) method:

- (5) Eliminate (through design): prefabrication; locate item at ground level;
- (4) Reduce (through design): design in edge protection; substitution of lesser hazard;
- (3) Reduce (engineering controls): local exhaust ventilation; temporary edge protection;
- (2) Inform of administrative procedure: 'contractor to provide method statement'
- (1) Control through PPE: 'contractor to provide PPE'

Data was compared for multimedia-user (experimental) and non-user (control) groups and also between novice and experienced designers. Collecting data before and after use of the multi-media tool enabled OSH knowledge, skills and abilities to be compared for both novice and experienced design professionals. Comparisons between experimental and control groups used the Mann-Whitney between group test. This tests for statistically significant differences between to separate groups (experimental/control). Changes before and after interventions within the same groups used the Wilcoxon Signed-Ranks Test, commonly associated with 'within group' 'pre-post' tests.

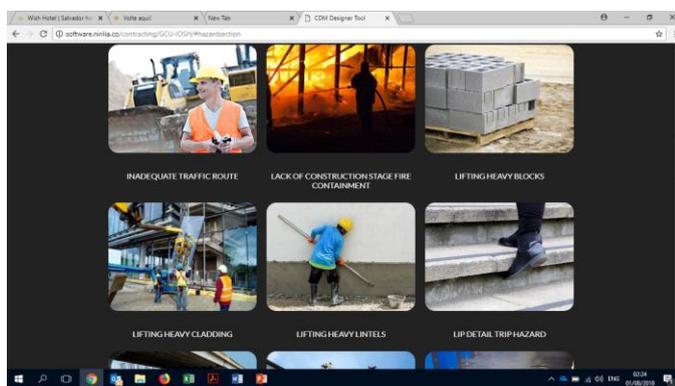


Figure 1 Screenshot of hazards on multimedia tool's homepage

3. Results

The hazards identified by the experimental group (before/after) are shown in Figure 2. This constitutes a total of 339 hazards (234 before + additional 105 after) for this group. The greatest increases in hazards identified were: high level lighting (n. 9); flooring COSHH (n. 8); paint COSHH (n. 8); welding steel frame (n. 8). The uplift in number of hazards identified by the experimental group amounts to 45% of the original number as a result of using the digital tool.

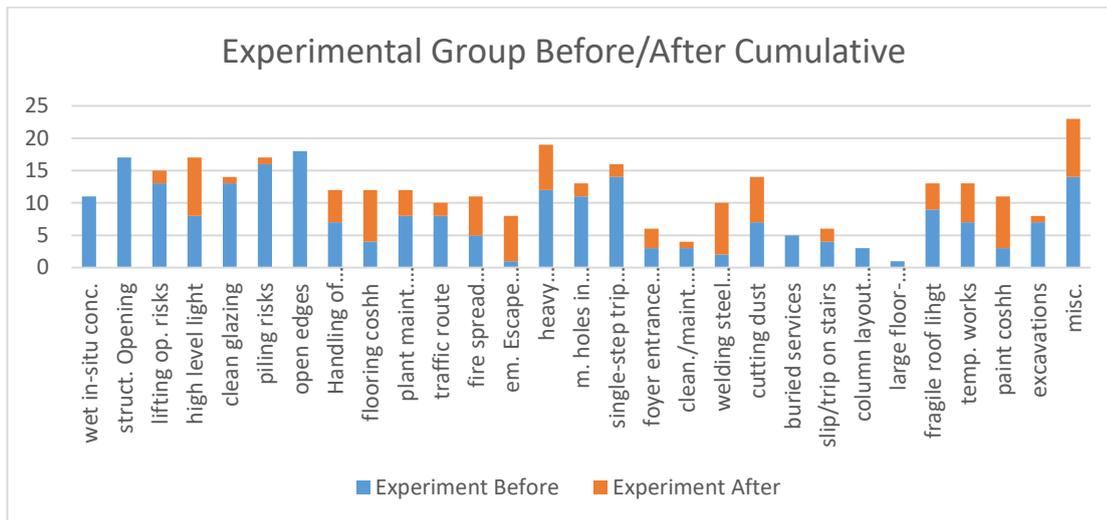


Figure 2 Experimental group number of hazards, before/after, cumulative

The hazards identified by the control group (before/after) are shown in Figure 3. This constitutes a total of 260 hazards (233 before + additional 27 after). The greatest increases in hazards identified for this group were: cutting dust (n. 4); wet in-situ concrete (n. 3); paint COSHH (n. 3). The uplift in number of hazards identified by the control group amounts to 12% of the original number as a result of searching the web, compared to the 45% rise for the experimental group.

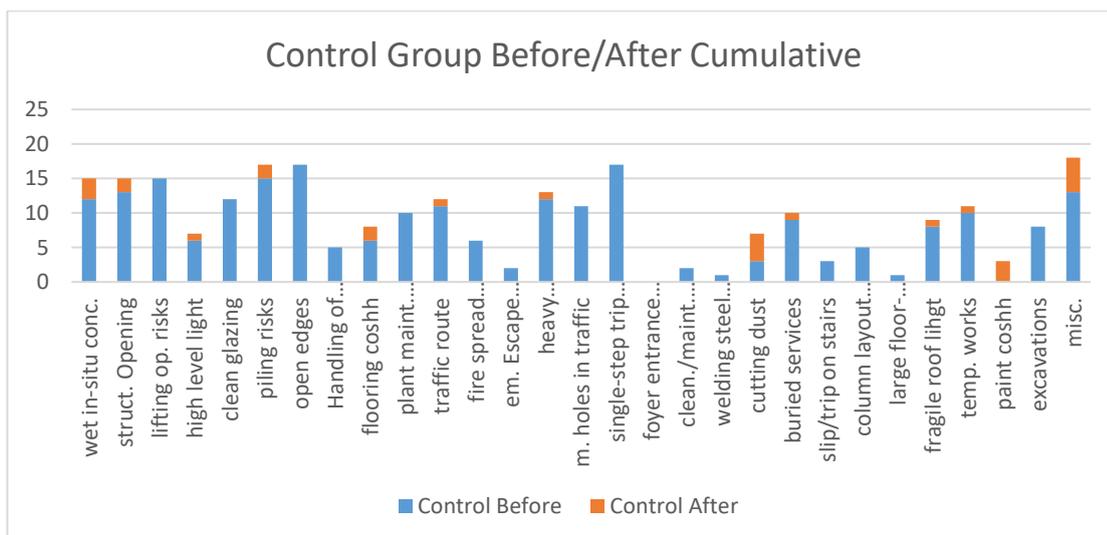


Figure 3 Control group number of hazards, before/after, cumulative

Filtering different groups (novice/expert) by experimental and control groups can provide further insights. However, some filters at this level of analysis did not produce much data for comparison. Specifically, the expert designers seem to have demonstrated a comprehensive understanding of the

hazards presented in the drawings. But comparing the groups still proved interesting.

Figure 4 shows additional hazards identified by novice designer’s post-intervention. This includes twin bars for each hazard-type; comparing the novice-experimental group (n. 70 additional hazards) with the novice-control group (n. 35 additional hazards). Visually, the bars for the novice-experimental group show better results, with more hazard-types (n. 16 more) identified post-intervention than the novice-control group. Conversely, hazard-types for the novice-control group improved at a better level than the novice-experimental group on only two occasions. There were four occasions where increases are tied between the two groups.

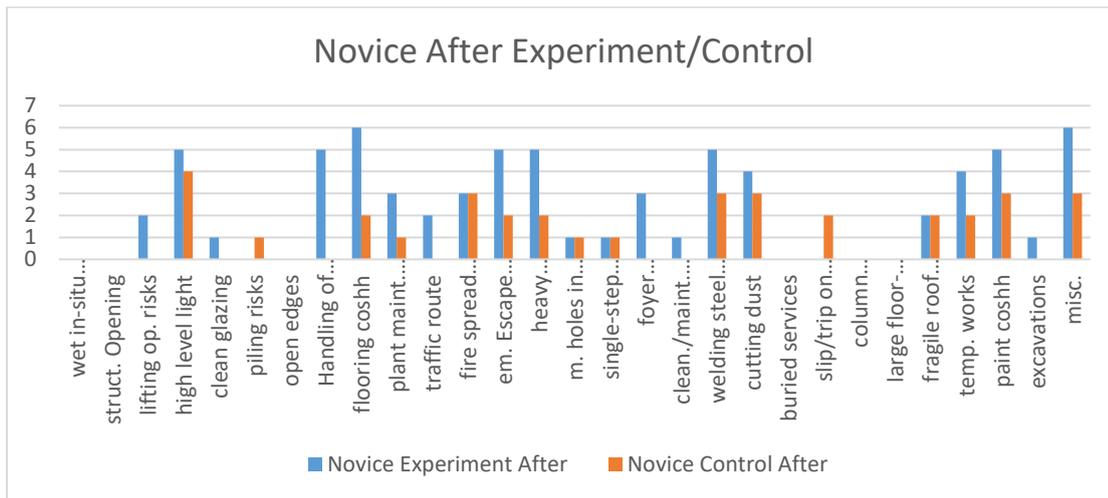


Figure 4 Novice number of hazards after intervention, experiment/control groups

Figure 5 shows additional hazards identified by expert designer’s post-intervention, comparing the expert-experimental group with the expert-control group. The experimental group identified 18 hazards post-intervention, compared to the control group who only identified a further nine hazards. Although there are few examples to compare at this level of filtering, it can be seen that there are more bars for the expert-experimental group (n. 10) than the expert-control group (n. 7), indicating a wider spread of hazards identified for those using the digital tool during the intervention.

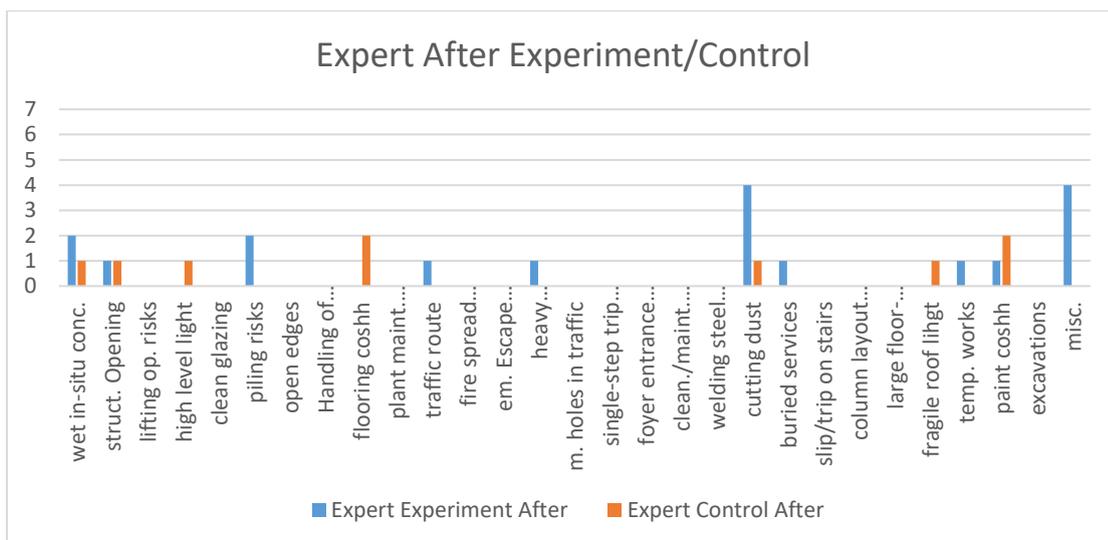


Figure 5 Expert number of hazards after intervention, experiment/control groups

The average (mean) number of project-specific hazards identified per designer was analysed for various groups. Figure 6 shows the change, from pre to post intervention, for all designers in the sample. This shows a clear rise in the mean hazard numbers for the experimental group, above that of the control

group. The pre-intervention mean values for experimental and control groups were 11.7 and 11.75 respectively (not statistically different). However, the experimental group increased to 16.95 post-intervention, whilst the control group increased to only 13.1. A Mann-Whitney statistical test for the difference between the two groups post-intervention returned a p-value of 0.017 (1-tailed). A Wilcoxon Signed-Ranks for the experimental group confirms a statistically significant change ($Z = -3.829$, $p < 0.001$), rejecting the null hypothesis (that designers will not improve their OSH effectiveness after using the digital tool).

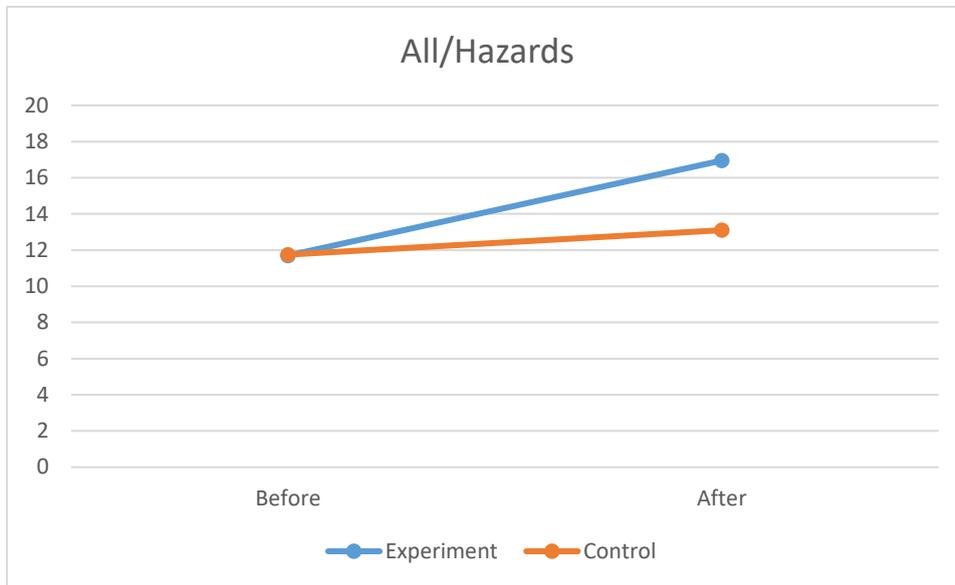


Figure 6 Mean hazard numbers, experiment/control

The data for novice and expert groups are shown in Figure 7. The graphs indicate what was anticipated i.e. novice designers identify (on average) less hazards than expert designers' pre-intervention, but increase post-intervention to near expert levels, whereas experienced designers show little increase as their average was already high to start with.

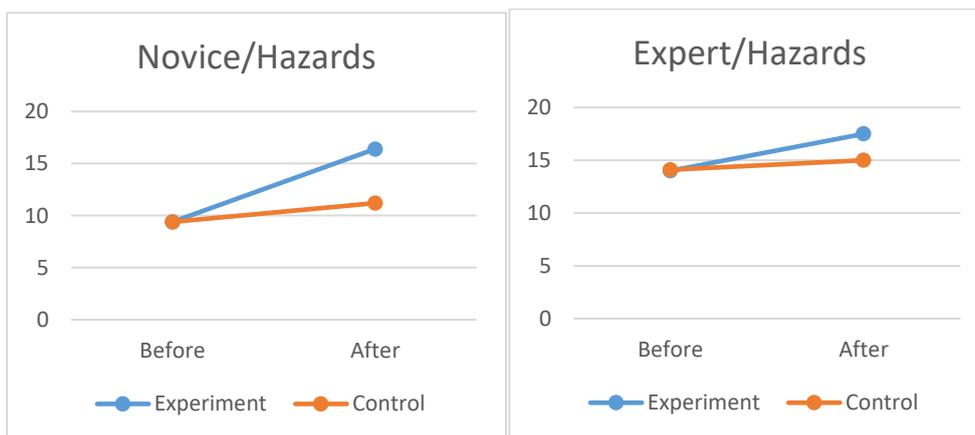


Figure 7 Mean hazard numbers, novice & expert experiment/control

The novice groups (experimental and control) both had a mean of 9.4 pre-intervention. The novice experimental post-intervention mean was 16.4 (within group: $Z = -2.810$, $p = 0.001$) and the corresponding control group was only 11.2 (between groups: $p = 0.018$), being statistically significant. The expert groups (experimental and control) pre-intervention, were 14 and 14.1 respectively, rising to 17.5 and 15. This small post-intervention rise was still statistically significant ($Z = -2.670$, $p = 0.002$). However, the difference between experimental and control groups was not ($p = 0.152$) meaning the null hypothesis could not be rejected. This could mean the difference was not great enough to satisfy the test

for the sample size, but another plausible explanation could be that expert designers didn't gain the same level of benefit as novice designers to distinguish them enough from the control group (as demonstrated by the small gap between experimental and control groups in the right hand graph of Figure 7).

The main reason for the two graphs in Figure 7 being side by side is to show that the novice experimental group's mean value surpassed the expert control group post-intervention. It was also closer to the higher expert experimental group mean than pre-intervention, as anticipated.

The mean scores for project-specific controls recommended by designers was analysed. Figure 8 shows the change, from pre to post intervention, for all designers in the sample. This shows a clear rise in the mean 'risk control scores' for the experimental group, above that of the control group (predictably, a similar result to the mean hazard numbers). The pre-intervention mean scores for experimental and control groups were 34 and 35.6 respectively (not statistically different). However, the experimental group increased to 55.85 post-intervention, whilst the control group increased to only 39.1. The between groups test post-intervention returned a p-value of 0.002 (1-tailed). The within group test confirms a statistically significant change ($Z = -3.825$, $p < 0.001$), rejecting the null hypothesis.

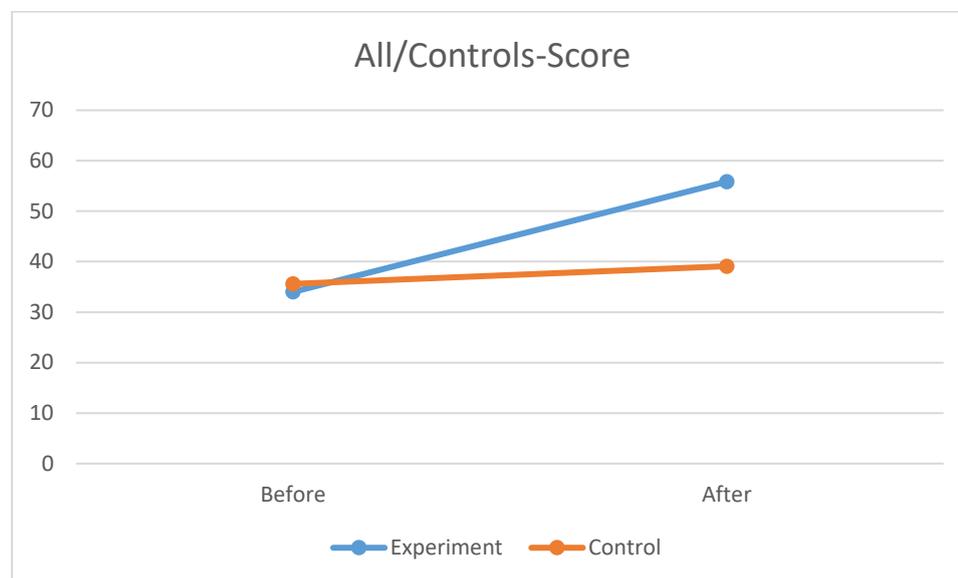


Figure 8 Mean controls-score, experiment/control

The data for novice and expert groups are shown in Figure 9. The graphs indicate what was anticipated in line with the hazard results i.e. novice designers had (on average) lower risk control scores than expert designers' pre-intervention, but increase post-intervention to near expert levels, whereas experienced designers show less of an increase as their average was already high to start with.

The novice groups (experimental and control) had means of 24.9 and 28.5 pre-intervention. The novice experimental post-intervention mean was 53.8 (within group: $Z = -2.805$, $p = 0.001$) and the corresponding control group was only 32.1 (between groups: $p = 0.007$), being statistically significant. The expert groups (experimental and control) pre-intervention, were 43.1 and 42.7 respectively, rising to 57.9 and 46.1. This post-intervention rise was statistically significant ($Z = -2.670$, $p = 0.002$). However, the difference between experimental and control groups was not ($p = 0.074$) meaning the null hypothesis could not be rejected. This repeats the result experienced with the hazard means and could likewise mean the difference was not great enough to satisfy the test for the sample size, or (per the hazards) that expert designers didn't gain the same level of benefit as novice designers to distinguish them enough from the control group (as demonstrated by the smaller gap between experimental and control groups in the right hand graph of Figure 9).

The two graphs in Figure 9, side by side shows again (per the hazard graphs) that the novice experimental group's mean score surpassed the expert control group post-intervention. It was also closer

to the higher expert experimental group mean than pre-intervention, as anticipated.



Figure 9 Mean controls-score, novice & expert, experiment/control

4. Discussion and Conclusions

The overall results clearly demonstrate that use of the multi-media digital tool (compared to merely using the internet) leads to improved hazard identification, in terms of number and scope of hazards. The digital tool's success is partly due to its visual format; in contrast to e.g. the HSE website, which generally lists hazards in bullet points or tables. This supports underpinning theories on the merits of visual methods of communicating OSH information (Hare, 2013; Lingard, 2015; Zhang, 2015).

The narrowing of the gap in hazards identified, between novice and experienced designers, was as expected. The pre-intervention hazards for the experts was 140 for experimental group and 139 for control group. The novice experimental group figures were 94 pre-interventions and a further 70 post-interventions. This confirms that 164 hazards were identified in total by novice designers exposed to the digital tool, which surpasses the pre-intervention figures of the experts (140).

The increase in mean hazards identified in the experimental group proved statistically significant and the null hypothesis when compared to the control group was rejected. This analysis provides confirmation of what the absolute hazard numbers suggest, that the post-intervention results are not down to chance but are most likely the result of exposure to the digital tool. The findings in relation to the tool's impact on mean hazard numbers for novice designers compared to experts showed conclusively that novice users benefited from using the tool. However, the tests for expert users were not so clear cut. Similar test results were replicated for the mean risk controls score, once again uniform results for novice designers but not for experts. The expert experimental group still showed visible increases on both mean hazards/controls graphs compared to the control group, therefore it can be concluded that it is still of use to expert designers but not to the same extent as for novice users. It may actually be worthwhile, if the digital tool is developed further, for expert designers to contribute to the content of the tool for the benefit of newly graduated (novice) designers as discussed by Metaxiotis and Samouilidis (2000).

The research has demonstrated that the digital tool (and related materials) is/are of most use to novice designers, such as students and new graduates. Adoption of the research outputs should foster long-term improvements in how new designers approach their designs with regard to DfOSH and their duties

under the CDM Regulations. The digital tool and hazard drawings need to be shared with tutors and trainers of architectural and engineering professions.

Integration of the tool with BIM technology would provide an ideal opportunity to further develop and test the theories around visualisation and the application of knowledge databases through visual means. This may also help to determine additional strategies to help designers gain more from use of the tool.

The hazards database and digital tool also provide a format more accessible than other similar databases on the internet, for sharing good practice. The recommended 'open' format (like a wiki) with designated gatekeepers e.g. IOSH Construction Group, will allow experienced designers to share their knowledge and help the next generation of designers so that such knowledge is not lost.

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