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Evidence of inconsistent results using current eye tracking glance and visit analysis standards

Matthew Sears [a], Omar Alruwaythi [b], Paul Goodrum [c,*]

[a] Department of Civil, Environmental and Architectural Engineering, University of Colorado Boulder, 1111 Engineering Drive, Boulder, CO 80309-0428, USA
[b] Department of Civil Engineering, Taibah University, Madinah 42353, Saudi Arabia
[c] Department of Construction Management, Colorado State University, Fort Collins, CO 80525, USA

A R T I C L E I N F O

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A B S T R A C T

Eye tracking glance analyses have been used to study the behavior of motor vehicle drivers for at least two decades and eye tracking is now emerging as an experimental protocol in construction research. Previous studies have identified relationships between driver glance behavior and performance, so existing motor vehicle driver glance analysis methods were applied to search for analogous relationships with construction craftworkers during a model assembly task. Eye tracking analysis software vendors have yet to adopt standardized eye tracking event detection algorithms, and researchers have historically reported insufficient details to render most eye tracking analyses reproducible. As a result, the purpose of the present work is to address the gap in knowledge in understanding the challenges encountered as a result of a lack of standardization. The methodology applied existing glance analysis methods to a study incorporating mobile eye tracking glasses, which made the experimental environment less controlled than a typical glance analysis study using a screen-based eye tracking system, such as a motor vehicle driver behavior study. A new noise filtering parameter, maximum off-stimulus fixations, was also introduced. The results show that the absence of standardized eye tracking parameters, such as minimum fixation duration, can lead to different statistical results. The study's primary contribution to the body of knowledge is that is identifies the need for standardization of eye tracking analyses to better ensure that future eye tracking studies be more consistent and reproducible.

1. Introduction

The current, industry-wide shortage of construction craftworkers is well documented. The age of the average construction craftworker is currently increasing at a rate four times the national average for other industries, largely due to young workers not entering the industry [36]. Declines in career and technical training in North America and a general lack of interest from young people to enter the industry have contributed to an aging workforce and a shortage of skilled craftworkers [42]. The craftworker shortage has negatively impacted construction project productivity for several decades, leading to increased costs, and schedule delays [8,12,13,36,37,56]. Now, more than ever, the industry needs innovative methods for improving craftworker productivity.

Previous studies have examined how the format of engineering information can improve craftworker performance, [9–11] and [58]. Dadi et al. [9–11] examined the cognitive load and the performance of 26 participants by utilizing 2D plan drawings, 3D CAD, and a 3D printed model to build scale model assemblies. The results indicate that greater cognitive demand was associated with 2D engineering deliverables and lower cognitive demands were associated with 3D engineering deliverables. Through application of a different experimental plan with structural ironworkers, Sweany et al. (2016) identified a statistically significant relationship between information format and task performance. When participants used the 2D plan set, they performed worst as compared to using either the 3D CAD model or the 3D physical print. While these previous research efforts, examined how different information formats can influence craft worker performance, the industry reality is that 2D information continues to be the most common format [6,20].

This research posits that productivity improvements could be realized through incremental improvements to traditional 2D construction drawings, the industry standard engineering information deliverable that has seen very little change in well over a century. Given the widespread use and familiarity of 2D construction drawings, any

* Corresponding author.
E-mail addresses: Matthew.H.Sears@colorado.edu (M. Sears), oruwaythi@taibahu.edu.sa (O. Alruwaythi), Paul.Goodrum@colostate.edu (P. Goodrum).

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improvements to the format or improved training in the use of format could have immediate, major impacts on industry-level productivity. Either improvement requires better understanding and measuring how craft workers seek the information they need. To that end, this research used eye tracking technology to investigate how professional pipefitters interacted with 2D drawings during a pipe model assembly task.

One method of investigating how craftworkers interact with 2D drawings is through the use of eye tracking technology. An extensive framework has been developed in the transportation industry for analyzing the glances of motor vehicle drivers [30,31], and glance analyses have been successfully conducted to assess many factors of driver performance [7,27,45,46,49,52,55,57]. The task of driving a motor vehicle is actually similar in many ways to assembling construction components. Motor vehicle drivers primarily receive visual information from looking at the road ahead, while receiving secondary visual information from: navigation devices, roadside signs, mirrors, etc. Similarly based on the authors' observations in the study's experiments, construction craftworkers primarily receive visual information from the components that they are actively assembling, while receiving secondary visual information from assembly drawings and measurement tools. Thus, the glace analysis framework developed previously for studying the behavior of motor vehicle drivers presents a promising method for investigating how construction craftworkers interact with engineering information deliverables.

Therefore, the research borrowed an existing, well-established eye tracking research framework from the transportation industry and applied it to assess construction craftworker interactions with construction drawings during a model assembly task. Our overarching goal is to gain a better understanding of craftworker interactions with engineering information, so that we may eventually suggest methods of improving craftworker performance. However, in applying the existing eye tracking framework to a construction model assembly task, we encountered several challenges that we believe are unlikely to have been encountered in previous motor vehicle eye tracking studies. Thus, the present work is an overview of those challenges, our methods for overcoming them, and our recommendations for the further standardization of eye tracking analyses.

2. Eye tracking terminology

Definitions for fixations, saccades, areas of interest, and other common eye tracking terms are provided by International Organization for Standardization (ISO) standard 15,007–1:2014 [30]. For the purpose of this work, we've adopted those widely accepted definitions and have not attempted to redefine them herein. ISO 15007-1:2014 also provides definitions for "glance" terminology; however, a glance is a higher-level construct than a fixation or a saccade, for example. The term "glance" is also not yet standard terminology, so its definition warrants further discussion. The glance related definitions provided by ISO 15007-1:2014 are reproduced below.

2.1. Glance

Maintaining of visual gaze within an area of interest, bounded by the perimeter of the area of interest; may be comprised of more than one fixation and saccades to and from it. Its duration is measured as "glance duration."

Merriam Webster defines a glance as, "to take a quick look at something" (Merriam-Webster.com [41]). While this colloquial definition is less precise, it is also an accurate description of a glance in the context of an eye tracking study.

2.2. Glance duration

Time from the moment at which the direction of gaze moves toward an area of interest to the moment it moves away from it.

The ISO standard provides definitions for glance related terminology; however, as discussed in Section 1.7.3, "visit" metrics are preferable to glance metrics in some cases. Therefore, we've adopted one technology supplier's definition of a visit, which is reproduced below (Tobii Pro AB 2019).

2.3. Visit

All the data between the start of the first fixation inside an Area of Interest (AOI) to the end of the last fixation in the same AOI. Note that a visit is simply a glance that does not include the initial saccade into an AOI. A visit may also include blinks.

2.4. On-stimulus/off-stimulus fixation

Whether a fixation was located on a stimulus image (drawing) or not.

2.5. Maximum off-stimulus fixations (MOSF)

The maximum number of sequential off-stimulus fixations permitted within a single visit. Note that "maximum off-stimulus fixations" is a concept developed by the authors for the present work.

3. Eye tracking data collection devices

Today, commercially available eye tracking data collection devices typically fall into one of two categories: screen-based devices, and mobile devices. Screen-based devices, which may also be called remote or desktop devices, are typically mounted on or near a computer monitor. These devices utilize video cameras, infrared sensors, or other sensing technology to capture eye data as a participant views images or videos on a computer monitor. Website and computer software user experience studies are a common use case for screen-based devices [16,18,19]; [59]; [32].

Mobile devices, on the other hand, usually take the form of binocular eye tracking glasses, as shown in Fig. 1. Eye tracking glasses are worn by a participant, similar to a common pair of corrective eyeglasses or sunglasses. Eye tracking glasses incorporate cameras directed at a participant's eyes, as well as a forward-facing camera that captures where a participant's head is directed within their environment. Eye tracking glasses are often connected to a cell phone or other data storage device that must be worn by a participant. However, because eye tracking glasses are not tethered to a computer, they provide participants with the freedom to move about their environment and look in any direction that they choose. The eye tracking data analyzed in the present work was collected with SMI Eye Tracking Glasses 2.0.

4. Eye tracking data collection in motor vehicle studies

The experimental environment for a motor vehicle driver behavior study is typically either a driving simulator or an actual motor vehicle.

Fig. 1. A typical pair of eye tracking glasses (SMI Eye Tracking Glasses 2.0).

Driving simulators incorporate a driver's seat, steering wheel, pedals, and other controls designed to mimic a motor vehicle. They also incorporate television screens, computer monitors, or other displays to create simulated driving conditions. More advanced simulators create a fully immersive experience through the use of an actual motor vehicle that has been retrofitted with visual displays instead of windows. Regardless of the level of sophistication of a driving simulator, simulated driving conditions are always displayed on visual screens, so eye tracking devices used in driving simulators are often classified as screen-based devices.

Historically, eye tracking data collection devices used in motor vehicle driver studies have fallen somewhere between screen-based devices and mobile devices. Some studies have coupled mobile eye tracking glasses with driving simulators [43], some have used eye tracking glasses with real (naturalistic) motor vehicles [54,57], and others have used specially equipped data collection vehicles. For example, the "100-Car Naturalistic Driving Study" is a frequently cited study in which video cameras were hidden within motor vehicles to capture driver behavior [14]. These vehicles cannot be considered screen-based data collection devices because the drivers had no screens to view. The cameras were also not mobile or wearable, yet they permitted the drivers to look in any direction within their environment.

5. Previous construction-related eye tracking studies

Several construction-related eye tracking studies have been conducted recently. Primarily, these studies have focused on safety, including hazard identification and mental fatigue [21,23–26,33–35,38,39]. Eye tracking has also been used to evaluate decision making with project planning visualizations [29], and to quantify human experience in architectural spaces [17].

6. Experimental protocol

In order to begin understanding the strategies that construction craftworkers use to obtain information from engineering drawings, we applied existing glance analysis methods to eye tracking data collected during a construction model assembly task. In this task, 20 professional pipefitters assembled a ½" diameter PVC pipe spool assembly. Descriptive demographic statics for the pipefitters are provided in Table 1. The pipefitters were provided with a set of isometric, black and white, 2D paper assembly drawings—the industry standard [6,20]—and a set of PVC fittings and pre-cut pipes. Each pipefitter was provided with the same set of drawings, and the set of drawings included ten sheets. The participants navigated through the drawings as needed, looking at each drawing as long as necessary, until they finished assembling the pipe spool assembly. Participants' performance in the experiments was measured by multiple performance measures including time completion, installation errors, rework, and direct work rates. In addition, eye tracking technology (Fig. 1) was used to quantitatively develop gaze plots and gaze heat maps to both visually and quantitatively measure how individuals interface both with their engineering deliverable and physical assemblies. To ensure accuracy of the eye tracking data, 3-point calibration was used by asking each participant to first look at a number of identified targets. Through the gaze of the participant at a certain target, the researchers calibrated the participant's eye by adjusting the cursor to the target point.

In total, 20 pipefitters were given a set ten drawings to build an assembly. The pipefitters' demographic statistics are shown in Table 1.

Table 1
Descriptive demographic statistics of pipefitters in the assembly task.

	Minimum	Mean	Median	Maximum	Std dev
Age (years)	20	34.3	31	60	11.8
Years of Experience	1	11.4	7.5	39	10.6

Initial results from the pipe spool assembly study were published by Alruwaythi, et al. [1], and the present work builds upon this previous work by diving deeper into the eye tracking data collected from craftworker interactions with the 2D drawings. [2] compared craftworker interactions with 2D and 3D engineering information formats at a high level, using total fixation counts and total gaze duration metrics. The present work advances the analysis by introducing the concept of eye tracking visits.

The ten reference images (the ten assembly drawings) each included a single area of interest that covered the entire image. Many eye tracking studies include multiple areas of interest within a single reference image, in order to increase granularity of the data collected. However, at this time, we were only interested in the patterns in which the craftworkers looked at the drawings as a whole, not the particular details that the craftworkers were looking at within the drawings. Therefore, we chose to create a single area of interest per drawing.

Fig. 2 shows a sample of one participant's glances to the construction drawings as they assembled the pipe spool assembly. In this figure, time progresses from left to right, and the durations that the participant looked at each of the drawings is represented by the width of the bars at the bottom. In this sample of data, the participant first looked at Drawing #1. Then they flipped the page to Drawing #2. Then they looked away from the drawings for a period of time before looking back at Drawing #1. They flipped to Drawing #3 for a short period before again looking back at Drawing #1. The relatively large gap of time between the period in which the participant looked at Drawing #2 and then back to Drawing #1 indicates that the participant was not looking at any drawings. In this case, the participant was looking at and assembling the pipe components. Large gaps of time in the eye tracking data such as this were encountered frequently during the pipe spool assembly study.

7. Applying the glance analysis framework to the construction model assembly task

In motor vehicle driver glance analyses, researchers have primarily been interested in off-road glance duration distributions, that is, the number of glances and the duration of glances off of the "road scene ahead." For example, many motor vehicle driver studies have used glance duration distributions to evaluate driver distraction [46,53]. Glance duration distributions have also been used to develop crash risk models [5,27,40]. One of the major findings from these studies is that a driver's crash risk increases significantly with each off-road glance that lasts longer than two seconds. As a result, the Alliance of Automobile Manufacturers has stated that, "single [off-road] glance durations generally should not exceed 2 seconds" [15]. Additionally, the NHTSA's driver distraction guidelines state that in-vehicle electronic devices should be "designed so that tasks can be completed by the driver while driving with glances away from the road of 2 seconds or less and a cumulative time spent glancing away from the roadway of 12 seconds or less" [44]. These recommendations are primarily responsible for the recent development of simplified mobile phone application user interfaces, such as Spotify's "Car View" [47] and AT&T's "DriveMode" [4]. These simplified user interfaces aim to make the use of mobile devices less distractive while driving.

Given the relationships identified between motor vehicle driver glance behavior and driver performance, we were interested to see if analogous relationships exist between craftworker glances to assembly drawings and their performance during a construction model assembly task. Of course, driving a vehicle is quite different from assembling construction components, but the tasks are similar in several ways. While driving a vehicle, a driver's visual attention is primarily focused upon the road ahead, and they obtain additional visual information during secondary tasks, such as looking at mirrors, manipulating a navigation device, looking at road signs, etc. Similarly, a craftworker's visual attention during an assembly task is primarily focused upon the

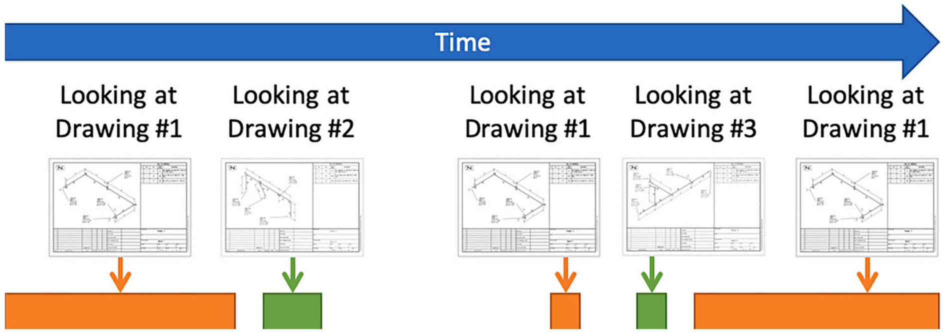

Fig. 2. Sample timeline of one pipefitter's glances to assembly drawings during the construction model assembly task.

components that they are assembling, while they obtain additional visual information from drawings, measurement tools, etc.

This paper's primary contribution to the existing body of knowledge is twofold. First, this work serves as the first application of the existing eye tracking glance/visit analysis methods defined in ISO 15007-1:2014 to a construction model assembly task. Second, this work illustrates how different eye tracking glance/visit analysis parameters chosen by researchers can lead to differing results and research conclusions.

8. Challenges

Our initial goal was to identify any relationships that might exist between craftworker glance behavior and construction model assembly task performance. However, in applying the standard methods of eye tracking glance analyses from the transportation industry to our model assembly task, we ran into several unanticipated challenges.

8.1. Event detection algorithms

A standard algorithm has not been adopted by eye tracking analysis software vendors for detecting fixations and other eye events from raw eye tracking data. In fact, Andersson, et al. compared no less than ten eye tracking event detection algorithms and was unable to satisfy their goal of naming a single "best event detection algorithm to recommend to researchers" [3]. Andersson, et al. found dramatic variation in detected event properties and stated that, "Researchers use algorithms such as these, sometimes seemingly mindlessly as they are often tightly integrated in the eye-tracking software." Such was the case with our model assembly study. We were aware that many event detection algorithms existed; however, our software provided no ability to use anything other than a default, built-in algorithm.

The eye tracking data in our model assembly study was collected with SMI Eye Tracking Glasses 2.0 and analyzed in SMI BeGaze v3.7. The precise event detection algorithm used by the BeGaze software is proprietary, and therefore unclear, but the BeGaze manual states that the event detector uses a "dispersion based algorithm" (SensoMotoric [51]). Selection of an appropriate event detection algorithm is beyond the scope of the present work; however, researchers should be aware that a multitude of algorithms exist, and that different algorithms or different algorithm parameters can lead to different results. We opted to use the default event detection algorithm parameters in the BeGaze software for our study.

8.2. Minimum fixation duration

Event detection algorithms often have customizable parameters. One of the most commonly available parameters is minimum fixation duration. ISO standard 15,007–1:2014 states that, "Fixations to an area of interest ≤120ms are physically not possible." We reference this as ISO 15007-1:2014 (Claim #1) in Table 2. However, the ISO standard provides no further explanation or evidence to support this claim. The standard also states that, "research shows that fixations can't be shorter than 100ms." We reference this as ISO 15007-1:2014 (Claim #2) in Table 2. This claim references [48]; however, we were unable to find anything within the cited work that supports this claim either. The distinction between the two claims in the ISO standard (120 ms minimum fixation duration versus 100 ms) is unclear, and the basis for those claims is also unclear. A revision of the ISO standard is currently under development, however, so it is possible that a future revision of the standard will provide clarification.

Table 2
Eye tracking analysis software minimum fixation duration settings.

Source	Default minimum fixation duration	Adjustable?
ISO 15007-1:2014 (Claim #1)	120 ms	N/A
ISO 15007-1:2014 (Claim #2)	100 ms	N/A
iMotions v7.2.0	100 ms	No
Tobii Pro Lab v1.118.1	60 ms	Yes
SMI BeGaze v3.7	50 ms	Yes

Interestingly, there is also no consensus amongst eye tracking analysis software vendors regarding an appropriate value for a minimum fixation duration. We reviewed three of the leading eye tracking analysis software packages to determine: a) what is this default minimum fixation duration setting, and b) can the minimum fixation duration be adjusted [28]; SensoMotoric [51]; Tobii Pro [60]. A summary is shown in Table 2. The default setting for iMotions was in accordance with one of the claims in the ISO standard, but the iMotions setting was not adjustable. Additionally, the default settings for the SMI and Tobii software packages were not in accordance with either of the claims in the ISO standard.

9. Glances versus visits

Glance and visit definitions are provided in Section 1.1. As shown in Fig. 3, a glance is simply a visit that includes the saccade leading into an AOI. Historically, many studies have preferred glance metrics over visit metrics, and ISO 15007-1:2014 pertains to the analysis of glances. However, it is not always possible to generate glances from visits, because visits are not always preceded by saccades. Many visits are preceded by blinks. The ISO standard states that in cases when it is not

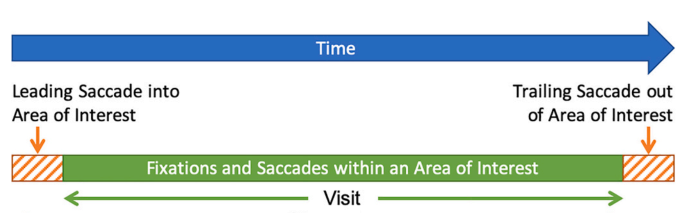

Fig. 3. Visit versus glance timeline.

technically possible to capture the leading transition into an area of interest (the leading saccade), an acceptable compromise is to include the trailing transition out of the area of interest, so long as the leading and trailing transitions are of equivalent length (equivalent duration). Therefore, we compared the leading and trailing saccades to determine if their durations were significantly different.

Table 3 shows that the durations of the leading and trailing saccades were significantly different, regardless of the minimum fixation duration used. Therefore, according to ISO 15007-1:2014, it was unacceptable to utilize the trailing saccades for the generation of glances. Additionally, many of our visits were both preceded and succeeded by blinks, so it would not have been possible to generate glances from these visits, even if the leading and trailing saccade durations had been equivalent. Depending upon the minimum fixation duration selected, only 72–82% of the visits could be used to generate glances. For this reason, we felt that it was most appropriate to analyze visit metrics in lieu of glance metrics.

9.1. Experimental environment and maximum off-stimulus fixations

In a typical motor vehicle eye tracking study, a participant's environment is well understood, static, and pre-defined. Participants remain seated in a vehicle or simulator and there are only so many directions in which they can look. Given a driver's constant point of reference, it is typically a relatively straightforward process to determine what a driver is looking at. For example, if a driver turns their head to the left, in the direction of their side mirror, then it is generally safe to assume that the driver is looking at their side mirror. Some motor vehicle studies have even relied upon head position alone to determine a participant's gaze location [14]. Additionally, in a motor vehicle study, areas of interest have static positions in space. Radios, mirrors, and GPS devices do not move.

In the construction model assembly task, however, participants were fitted with mobile eye tracking glasses, and they were free to move about their environment and look in any direction. Additionally, the objects within their environment were not static. They were able to move the pipe components, move the assembly drawings, and flip between the pages of the drawings. As such, we could not rely on head position alone to determine whether a participant was looking at a construction drawing, let alone which construction drawing they were looking at. The freedom for the participants to manipulate objects within their environment was necessary for our study. However, we believed that the experimental setup also created the potential for noise within the collected eye tracking data.

The experimental design included ten assembly drawings as reference images. The physical dimensions of the drawings were 11"x17", so they accounted for a relatively small area within a participant's entire field of vision. Upon reviewing the recorded data, we noticed that fixations on an assembly drawing, heretofore known as "on-stimulus fixations," would often be intermingled with fixations that were very close to the drawing, yet technically outside of the perimeter of the drawing, heretofore known as "off-stimulus fixations." An example of this is shown in Fig. 4.

Table 3
Visit leading and trailing saccade durations for common minimum fixation durations, all 20 participants, MOSF = 0.

Minimum fixation duration	Mean leading saccade duration (visits with leading saccade only)	Mean trailing saccade duration (visits with trailing saccade only)	t-value	*p*-value
0 ms	150.7 ms ($n = 4396$)	201.8 ms ($n = 4375$)	−15.7	<0.001
50 ms[a]	150.7 ms ($n = 4392$)	201.8 ms ($n = 4371$)	−15.7	<0.001
60 ms[b]	149.1 ms ($n = 4390$)	200.6 ms ($n = 4356$)	−15.9	<0.001
100 ms[c,d]	123.6 ms ($n = 4327$)	180.7 ms ($n = 4077$)	−18.1	<0.001
120 ms[d]	109.1 ms ($n = 4130$)	166.6 ms ($n = 3784$)	−18.1	<0.001

[a] Default duration in SMI BeGaze software.
[b] Default duration in Tobii software.
[c] Duration required by iMotions software.
[d] Duration recommended by ISO standard 15,007–1:2014.

Fig. 4 shows part of one visit to an assembly drawing from one participant in the study. The points on the drawing represent the participant's fixation points, labeled in chronological order. In this case, the participant looked at the drawing during fixation points #1–3, then looked just beyond the perimeter of the drawing at fixation point #4, and then back at the drawing during fixation points #5–6. Fixation point #4 was an off-stimulus fixation, and the rest of the fixation points were on-stimulus fixations. The duration of each fixation is represented by the width of the bars at the bottom of the figure, and mean fixation durations are provided in Table 3. The mean duration of on-stimulus fixations was 267 ms, while the mean duration of off-stimulus fixations was 217 ms.

It is possible that participants did in fact make frequent, off-stimulus fixations while looking at the drawings. However, it's also entirely possible that the participants were actually looking at the drawings during the recorded off-stimulus fixations, and that the off-stimulus fixations were simply noise resulting from the size of the drawings and the precision of our eye tracking data collection hardware. Upon visual inspection of the recorded data, it did not appear as though participants were attempting to do anything other than look at the drawings when they made these off-stimulus fixations. Therefore, we introduced a new noise filtering parameter, maximum off-stimulus fixations (MOSF). This parameter specifies the maximum number of sequential off-stimulus fixations that are permissible within a visit. The parameter may be set to any whole number and specifying an MOSF value greater than zero has the effect of filtering out off-stimulus fixations, thus treating them as noise that is ignored.

The definition of a glance provided by ISO 15007-1:2014 (see Section 1.1) has no concept of off-stimulus fixations. Therefore, generating glances with an MOSF value of zero would produce glances in accordance with the ISO standard. The scanpath shown in Fig. 4 would produce two glances/visits when $MOSF = 0$, and a single glance/visit when $MOSF \geq 1$.

10. Study measurements

We developed a custom JavaScript web application for analyzing visits from eye tracking data. The application is named Visual Eyes, and the source code is available at the project repository on GitHub [50]. Visual Eyes supports the iMotions and SensoMotoric Instruments (SMI) data file formats, and all results presented herein were produced from data exported from the Visual Eyes application.

11. Fixation durations

Minimum fixation duration is a parameter selected by a researcher, so one goal of the present work was to gain a better understanding of the influence that minimum fixation duration has on an eye tracking analysis. We first calculated fixation duration summary statistics, which are shown in Table 4. The percentiles indicate the proportion of the eye tracking data that would have been excluded by selecting a particular minimum fixation duration. For example, if we opted to use a minimum fixation duration of 120 ms, then our analysis would have excluded 26% of the recorded fixation points, while a minimum fixation duration of 50 ms would have excluded virtually none of the recorded data. Fixations were classified as either "on-stimulus," indicating that the participant was looking at one of the ten construction assembly drawings, or "off-stimulus," indicating that they were looking at something other than the drawings. The on-stimulus and off-stimulus fixation duration distributions are shown in Fig. 5.

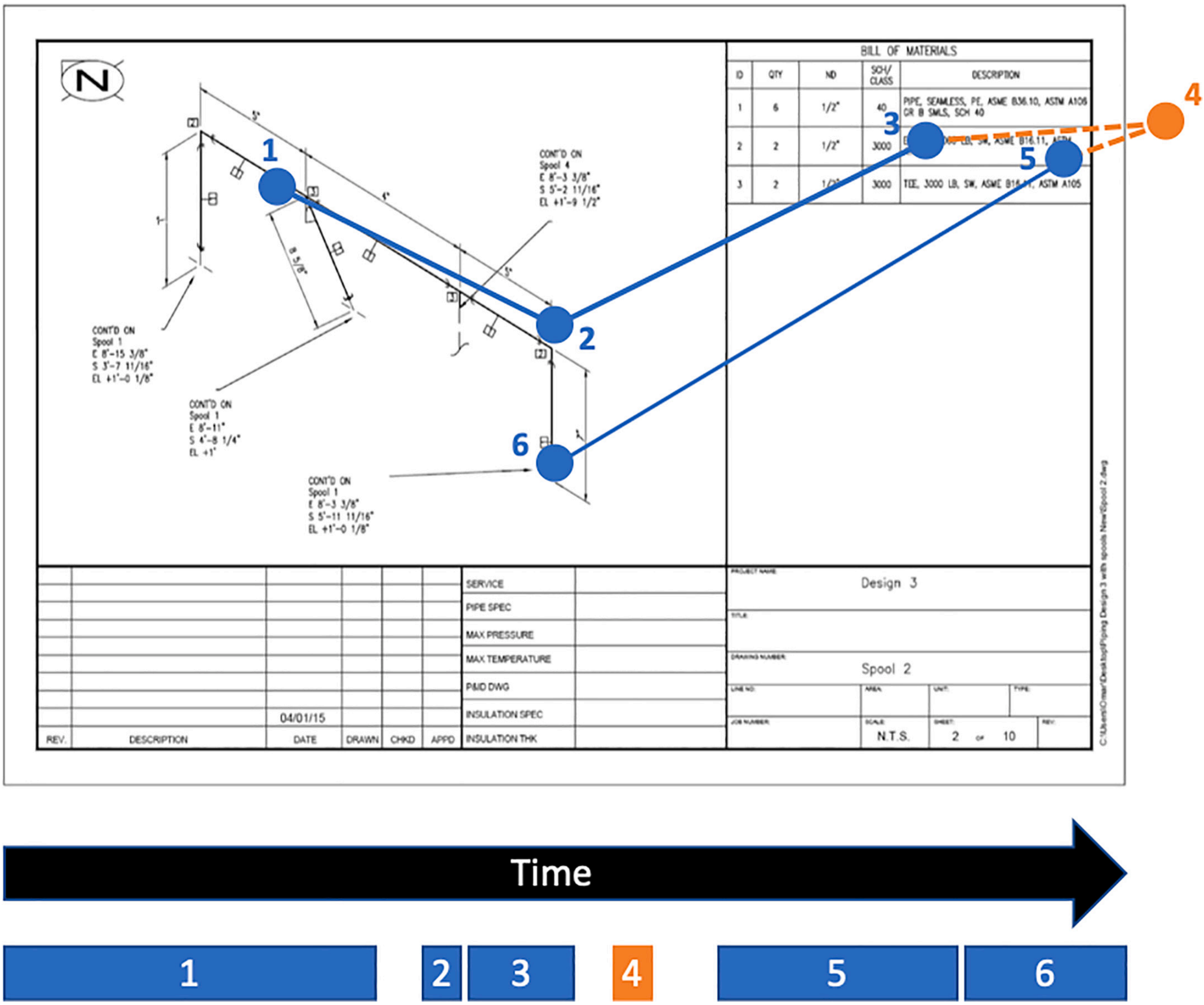

Fig. 4. Sample of fixations with one off-stimulus fixation.

Table 4
Fixation duration summary statistics, all 20 participants.

	On-stimulus	Off-stimulus	All fixations
Number of Fixations (n)	51,265	84,933	136,198
50 ms percentile	0.03%	0.09%	0.06%
60 ms percentile	0.70%	1.32%	1.08%
100 ms percentile	14.11%	20.82%	18.30%
120 ms percentile	26.04%	34.42%	31.26%
Minimum Duration	16 ms	0 ms	0 ms
25th Percentile Duration	117 ms	100 ms	116 ms
50th Percentile Duration (Median)	183 ms	165 ms	166 ms
75th Percentile Duration	315 ms	249 ms	281 ms
Maximum Duration	4183 ms	8132 ms	8132 ms
Mean Duration	267 ms	217 ms	236 ms
Skewness (Pearson method)	4.06	5.94	5.00
Kurtosis (Fisher method)	28.69	89.45	54.69

12. Visit generation

First, a user maps fixation points to stimulus images using software provided by the eye tracking hardware manufacturer, or a third-party. In our case, the SMI BeGaze software was used, and the reference images were the ten assembly drawings. Next, the eye tracking data is uploaded to Visual Eyes, and the user specifies a minimum fixation duration (MFD) and a maximum off-stimulus fixations value (MOSF) to generate visits from the eye tracking data. Fixations with a duration less than the specified minimum fixation duration are simply ignored. The process that Visual Eyes uses to generate visits is rather simple. It is illustrated in Fig. 6 and summarized in Section 2.3 below.

13. Visit generation process

1. The first visit begins with the first recorded fixation point.
2. If another (subsequent) fixation point exists, then Visual Eyes checks whether the next fixation point landed on the same stimulus image (assembly drawing) as the previous fixation point. This is determined by a simple string comparison of the names of the stimulus images that the fixation points were mapped to.

a. If the two fixation points landed on the same stimulus image, then Visual Eyes checks whether the fixation point duration satisfies the minimum fixation duration.

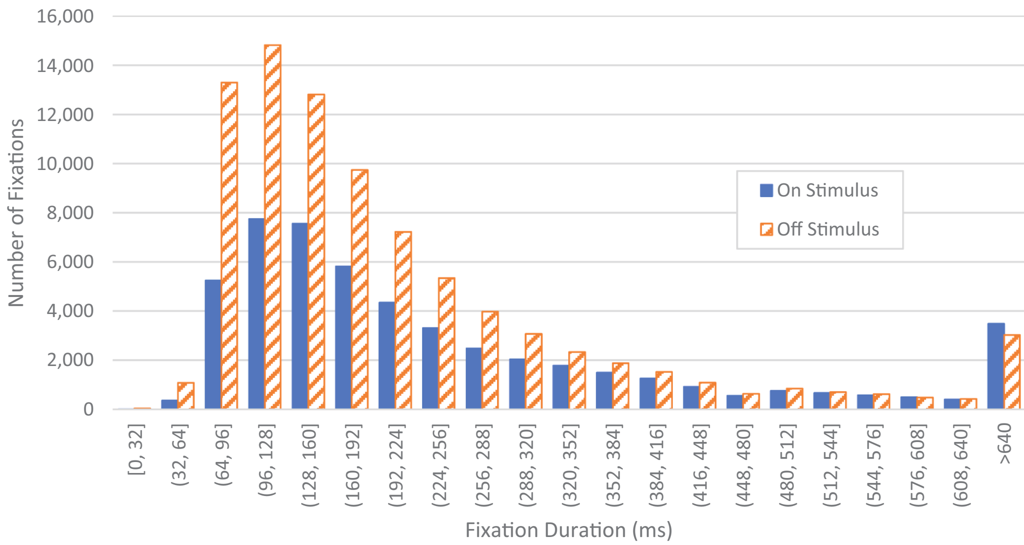

Fig. 5. Fixation duration distribution, all 20 participants.

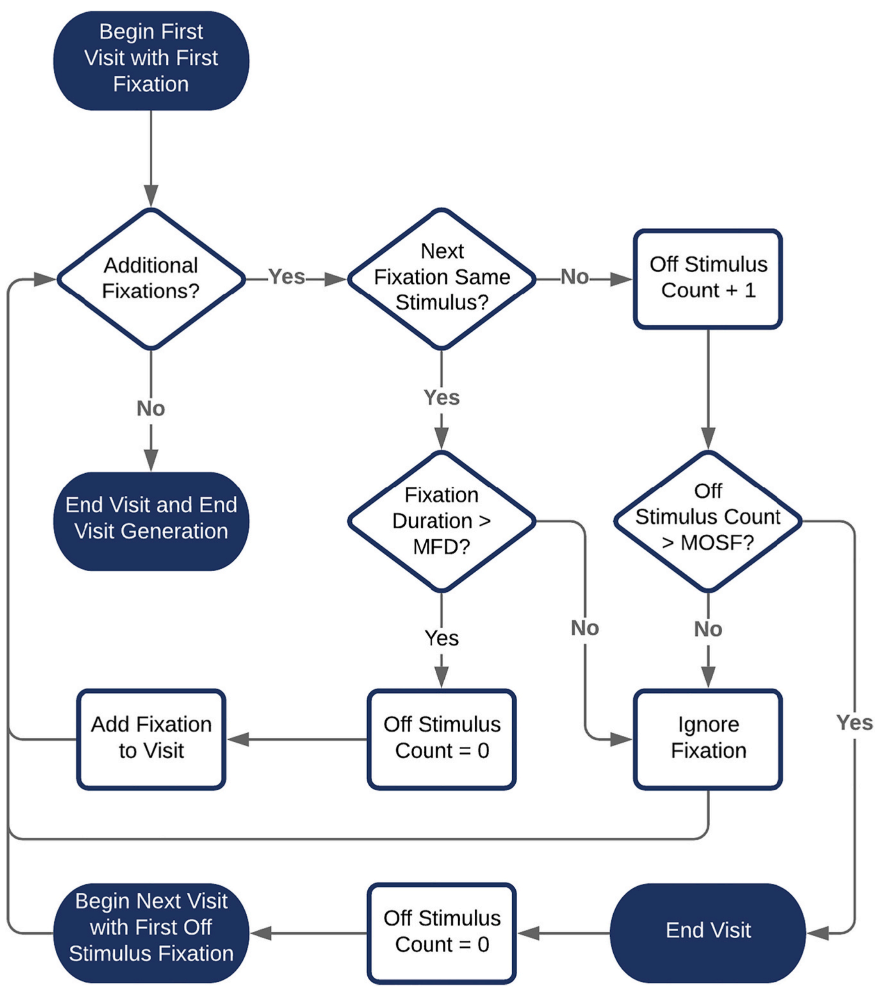

Fig. 6. Visit generation process.

i. If the **minimum fixation duration** is NOT satisfied, then the fixation point is ignored, and the process continues at Step 2.
ii. If the **minimum fixation duration** is satisfied, then the fixation point is added to the visit, the **off-stimulus count** is reset to zero, and the process continues at Step 2.

b. If the next fixation point did not land on the same stimulus image as the previous fixation point, then the next fixation point is NOT added to the visit, and the **off-stimulus count** is incremented by one.

i. If the **off-stimulus count** is NOT greater than the **maximum off-stimulus fixations**, then the process continues at Step 2.
ii. If the **off-stimulus count** is greater than the **maximum off-stimulus fixations**, then the visit is terminated, and the **off-stimulus count** is reset to zero. If additional fixation points remain then the next visit begins with the next fixation point, and then the process continues at Step 2.

3. The process concludes when no fixation points remain. If a visit is being generated, then it is terminated.

14. Results

Since the eye tracking community has not adopted a standard minimum fixation duration value, we generated visits using five different minimum fixation duration values. We used the four durations commonly used by eye tracking analysis software vendors listed in Table 2, as well as a duration of zero for reference. Table 5 lists the number of visits generated in each case, as well as the mean and median duration of the generated visits.

After generating visits "normally" ($MOSF = 0$) for each of the minimum fixation durations, we calculated visits several more times, using an MOSF value of one through five. We did this to see how the parameter influenced the generation of visits. The number of visits generated is shown in Fig. 7, as a function of minimum fixation duration (MFD) and maximum off-stimulus fixations (MOSF). Note that the top blue line ($MOSF = 0$) corresponds to the number of visits generated in Table 5. The mean visit durations are shown in Fig. 8, also as a function of MFD and MOSF.

15. Relationship with assembly task completion time

Our purpose of analyzing craftworker interactions with construction assembly drawings was to determine whether a relationship exists between craftworker eye gaze patterns and performance. One measure of performance that we were particularly interested in was the amount of time that the participants required to complete the construction model assembly task. We wanted to determine whether a relationship existed between assembly task completion time and mean visit duration. However, we did not have a single optimal minimum fixation duration value to use, so we computed Pearson correlation coefficients for each minimum fixation duration. We were also interested to see what impact MOSF had on the relationship, so we also computed Pearson correlation coefficients for each combination of the minimum fixation durations and MOSF values. The results are shown in Table 6. In order to illustrate these relationships, we selected three of the cells from Table 6, which are shaded gray, and plotted the individual data points in Fig. 9.

Table 5
Visits generated for common minimum fixation durations, all 20 participants, MOSF = 0.

	Minimum fixation duration				
	0 ms	50 ms[a]	60 ms[b]	100 ms[c,d]	120 ms[d]
Visits Generated (Count)	6098	6094	6062	5529	5052
Mean Visit Duration	2918 ms	2920 ms	2934 ms	3173 ms	3436 ms
Median Visit Duration	1842 ms	1842 ms	1858 ms	1991 ms	2157 ms
Visits Preceded by Blink	1687 (28%)	1687 (28%)	1657 (27%)	1182 (21%)	900 (18%)
Visits Preceded and Succeeded by Blink	678 (11%)	678 (11%)	662 (11%)	423 (8%)	296 (6%)

[a] Default duration in SMI BeGaze software.
[b] Default duration in Tobii software.
[c] Duration required by iMotions software.
[d] Duration recommended by ISO standard 15,007–1:2014.

16. Discussion

16.1. Minimum fixation duration

The leading eye tracking software analysis packages that we reviewed each had a different default minimum fixation duration. Further, most of those durations were not in accordance with the durations recommended in ISO standard 15,007–1:2014, and the ISO standard itself was not clear in specifying a single appropriate minimum fixation duration to use in eye tracking analyses. Thus, there is no guarantee that any two historic eye tracking glance/visit analyses were conducted using the same minimum fixation durations unless the authors of the studies explicitly stated the minimum fixation durations that were used. This is problematic because, as shown in Table 6, different minimum fixation durations can lead to different results.

Table 5 and Fig. 7 show that the number of visits generated decreased as the minimum fixation duration increased. This is logical for two reasons. One, filtering out short duration fixations means that there were simply fewer fixation points from which to generate visits. Additionally, many of the short duration fixations were off-stimulus fixations. Thus, when off-stimulus fixations were filtered out of the data, they no longer counted toward the maximum off-stimulus fixations permitted within a visit. Therefore, as the minimum fixation duration increased, sequential visits were more likely to be combined. As a result, it was only possible for the number of visits generated to decrease as minimum fixation duration increased. For the same reasons, as the minimum fixation duration increased and adjacent visits were combined together, it was only possible for the mean visit duration to increase. The relationship between minimum fixation duration and mean visit duration is illustrated in Fig. 8.

16.2. Glances versus visits

Table 3 showed that the leading saccades into a visit and the trailing saccades out of a visit had significantly different durations. This meant that we were unable to generate glances for a considerable number (18–28%) of the recorded visits. We felt that analyzing visits in lieu of glances was an acceptable solution; however, we also acknowledge that much of the existing literature pertains to the analysis of glances. Unfortunately, it has not been standard practice for researchers to report leading and trailing saccade durations, so we cannot say whether the saccade duration difference that we observed was typical for an eye tracking study. We recommend, however, that researchers report leading and trailing saccade durations in future eye tracking visit/glance analyses. Additionally, we recommend that future studies report the proportion of visits preceded by blinks or other events, as we also reported in Table 3. At a minimum, future glance analyses should report whether leading and trailing saccade durations were compared to confirm whether the analysis of glances was appropriate.

16.3. Maximum off-stimulus fixations

Maximum off-stimulus fixations (MOSF) was a new parameter introduced by the present work. We created this parameter because we believed that some of the off-stimulus fixation points in our dataset were actually noise resulting from the experimental design. By generating visits with several different MOSF values, we were able to see how filtering out the suspected noise impacted the results of our study.

Fig. 7 shows that the number of visits generated decreased as MOSF increased. This is logical because MOSF specifies the number of sequential off-stimulus fixation points that are permissible within a single visit. As that number increases, adjacent visits are less likely to be divided by off-stimulus fixations and are therefore combined into a single visit. The number of visits generated can only decrease as MOSF

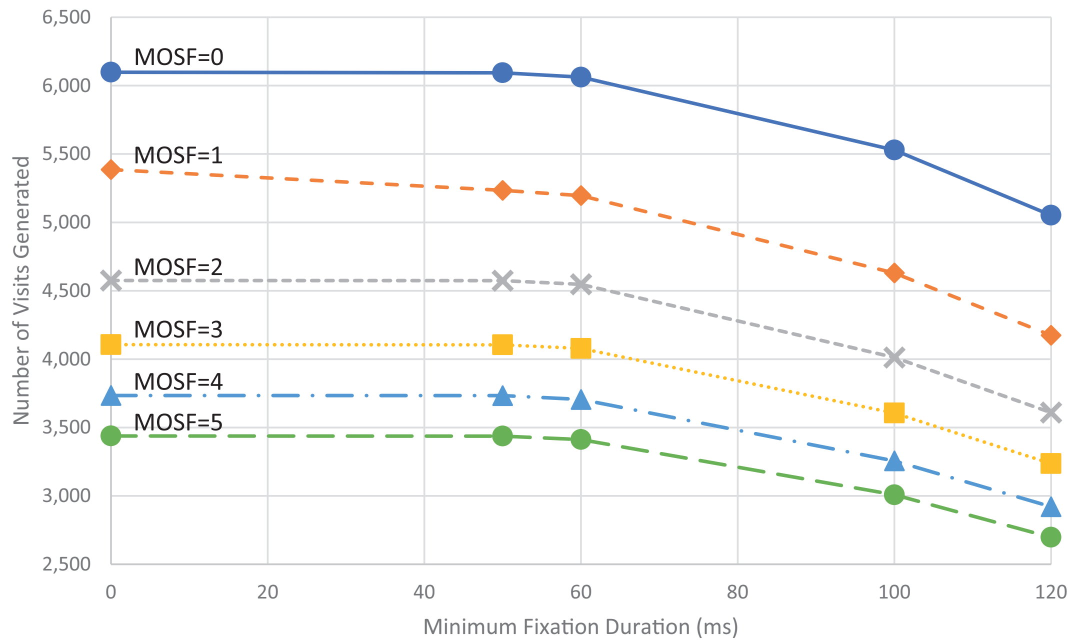

Fig. 7. Number of visits generated as a function of minimum fixation duration and maximum off-stimulus fixations (MOSF).

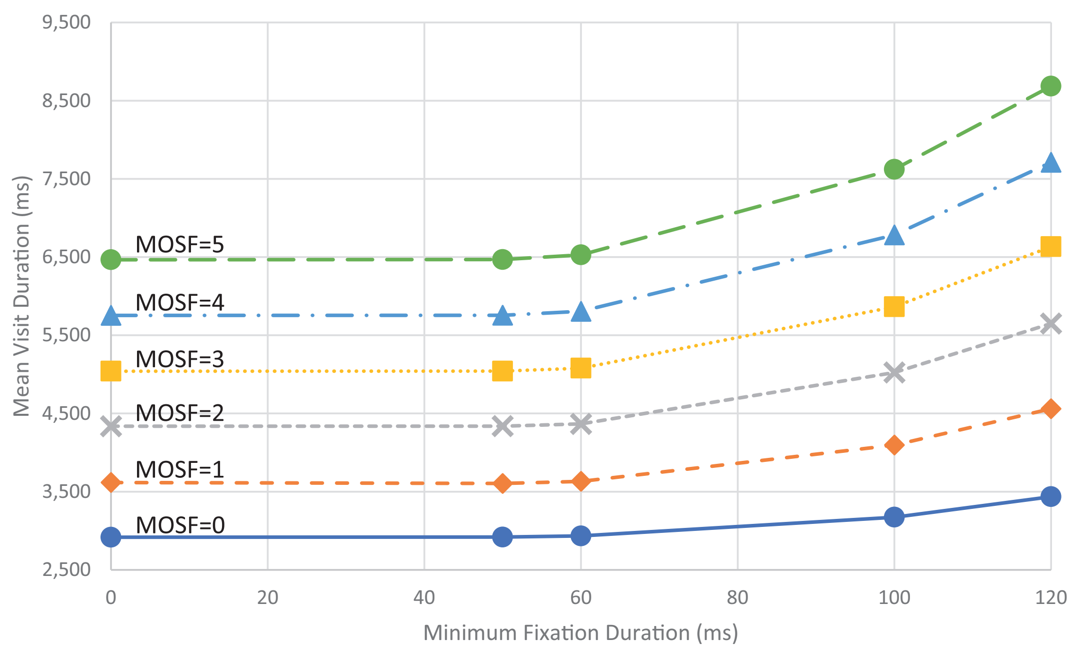

Fig. 8. Mean visit duration as a function of minimum fixation duration and maximum off-stimulus fixations (MOSF).

increases. For the same reasons, the mean visit duration increased as MOSF increased.

16.4. Relationship with assembly task completion time (measure of performance)

Table 6 shows how the relationship between assembly task completion time and mean visit duration varied as minimum fixation duration and maximum off-stimulus fixations (MOSF) varied. First, it is important to note that we did not conduct this series of correlation tests in order to select an optimal minimum fixation duration or an optimal MOSF value. Attempting to select optimal parameters from this single post-hoc analysis would be inappropriate. We conducted these tests and prepared Table 6 simply to show that different minimum fixation durations and different MOSF values can lead to different results—nothing more.

When $MOSF = 0$ (the top row of Table 6), moving from left to right in the table, as the minimum fixation duration increased up to 120 ms, the relationship became stronger. This is the result that we would expect to see, if there was in fact a linear relationship between assembly task completion time and mean visit duration, and if the fixation points with a duration of less than 120 ms were in fact noise, as purported by the ISO 15007-1:2014 standard. In other words, as we filtered out more of the supposed noise, the relationship between assembly task completion time and mean visit duration became stronger. Given this result, it is possible that a minimum fixation duration of 120 ms is more appropriate than 50

Table 6
Pearson correlation test results between mean visit duration and assembly task completion time.

Maximum off-stimulus fixations	Minimum fixation duration				
	0 ms	50 ms[a]	60 ms[b]	100 ms[c,d]	120 ms[d]
0	$R^2 = 0.098$ $p = 0.180$	$R^2 = 0.097$ $p = 0.182$	$R^2 = 0.096$ $p = 0.184$	$R^2 = 0.140$ $p = 0.104$	$R^2 = 0.190$ $p = 0.055$
1	$R^2 = 0.149$ $p = 0.093$	$R^2 = 0.148$ $p = 0.094$	$R^2 = 0.150$ $p = 0.091$	$R^2 = 0.187$ $p = 0.057$	$R^2 = 0.247$ $p = 0.026$
2	$R^2 = 0.217$ $p = 0.038$	$R^2 = 0.216$ $p = 0.039$	$R^2 = 0.216$ $p = 0.039$	$R^2 = 0.207$ $p = 0.044$	$R^2 = 0.175$ $p = 0.066$
3	$R^2 = 0.241$ $p = 0.028$	$R^2 = 0.240$ $p = 0.028$	$R^2 = 0.240$ $p = 0.028$	$R^2 = 0.236$ $p = 0.030$	$R^2 = 0.194$ $p = 0.052$
4	$R^2 = 0.242$ $p = 0.028$	$R^2 = 0.244$ $p = 0.027$	$R^2 = 0.245$ $p = 0.026$	$R^2 = 0.259$ $p = 0.022$	$R^2 = 0.199$ $p = 0.049$
5	$R^2 = 0.213$ $p = 0.041$	$R^2 = 0.217$ $p = 0.039$	$R^2 = 0.222$ $p = 0.036$	$R^2 = 0.212$ $p = 0.041$	$R^2 = 0.177$ $p = 0.064$

[a] Default duration in SMI BeGaze software.
[b] Default duration in Tobii software.
[c] Duration required by iMotions software.
[d] Duration recommended by ISO standard 15,007–1:2014.

ms. However, determining an optimal minimum fixation duration is beyond the scope of the present work.

As MOSF increased from zero to one, the correlations became stronger for each of the minimum fixation durations. This is also the result that we would expect if there was in fact a linear relationship between assembly task completion time and mean visit duration, and if single off-stimulus fixation points were in fact typically noise. Moving further down the table, as MOSF continued to increase, the correlations typically became stronger, before becoming weaker at $MOSF = 5$. Again, from the present work alone, we are unable to determine whether an optimal MOSF value exists, let alone what an optimal MOSF value would be. However, these results suggest that off-stimulus fixations may in fact often be noise. Future efforts may determine that an optimal MOSF noise filtering parameter is greater than zero, and perhaps less than five.

We selected three of the cells from Table 6 to illustrate how the relationship between assembly task completion time and mean visit duration varied as minimum fixation duration and MOSF varied (Fig. 9). Each of the three groups included 20 points, representing each of the 20 participants in the study. The assembly task completion times were constant, so the plotted points only differ in their ordinal (y) co-ordinates. From these results, we see that if a researcher had used the SMI BeGaze default minimum fixation duration of 50 ms and an MOSF value of zero, then they would have likely concluded that no relationship existed between assembly task completion time and mean visit duration ($R^2 = 0.097, p = 0.182$). On the other hand, if a researcher had used a minimum fixation duration of 120 ms, as suggested by ISO 15007-1:2014, and an MOSF noise filtering value of 1, then they very likely would have concluded that a significant relationship did exist between assembly task completion time and mean visit duration ($R^2 = 0.247, p = 0.026$).

17. Conclusion

The purpose of the present work was to present the challenges that we encountered in applying existing eye tracking glance analysis methods to a construction model assembly task. The first challenge that we encountered was a general lack of standardization in the algorithms and parameters associated with computing fixations from raw eye

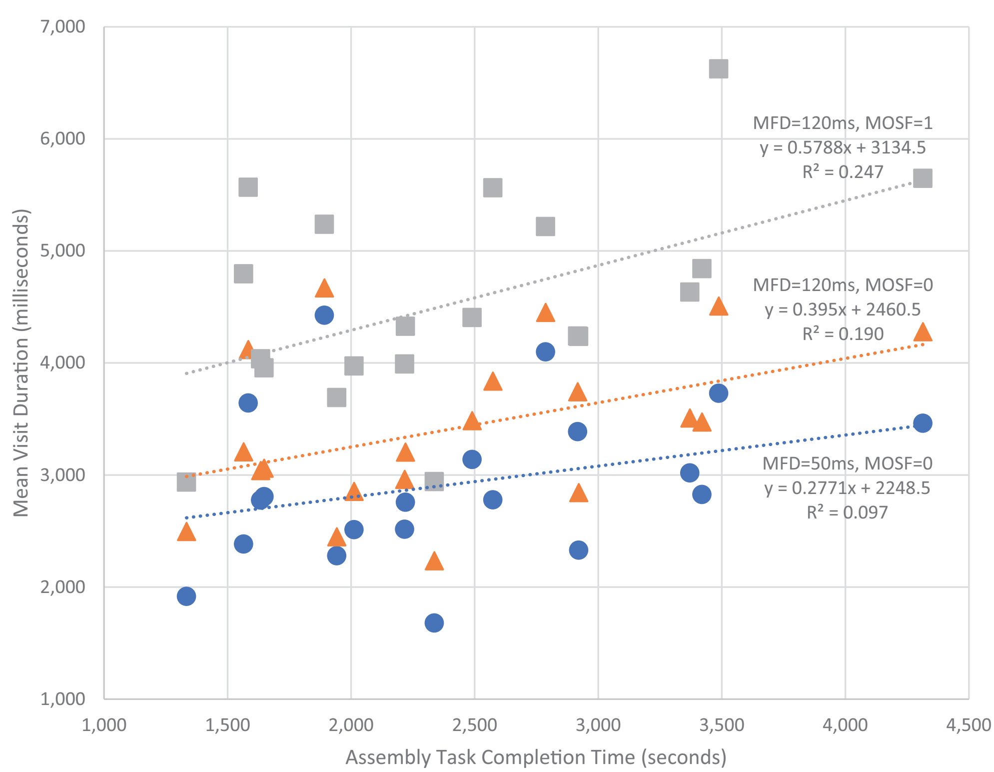

Fig. 9. Assembly task completion time relationships, all 20 participants, three combinations of minimum fixation duration (MFD) and maximum off-stimulus fixations (MOSF).

tracking data. We showed how different values for these parameter settings, such as minimum fixation duration, have a major impact on the generation of eye tracking visits. The experimental environment for our pipe spool assembly study also differed from the environment of a typical motor vehicle study. As a result, our data included many fixation points that we believed to be noise. We developed a new parameter, maximum off-stimulus fixations (MOSF), in order to filter out this supposed noise. We conducted a series of correlation tests using several values for minimum fixation duration and maximum off-stimulus fixations. Results of the correlations tests illustrated how the values selected for the parameters can impact the results of eye tracking glance/visit analyses. Additionally, the results were consistent with our hypothesis that the off-stimulus fixations within our data were in fact noise.

This work was the first effort to apply the existing eye tracking glance analysis framework from the transportation industry, as defined by ISO 15007-1;2014, to the domain of construction productivity. We developed an open source web application for applying the existing methods, and we expanded upon those methods by introducing the maximum off-stimulus fixations noise-filtering parameter. We investigated the relationship between mean visit duration and a single performance metric. However, mean visit duration is only one of many metrics produced by the Visual Eyes software, so we have really only scratched the surface of the analyses that are now possible with Visual Eyes and the eye tracking data that we currently possess. Our future work will investigate additional eye tracking visit metrics and their relationships with construction craftworker performance and demographics. We are also currently using Visual Eyes to analyze participant behavior during other construction-related tasks, such as worksite hazard recognition. Development of the Visual Eyes application is ongoing, and we encourage other eye tracking researchers to use the app and to contact the authors for support and with any suggestions for improvements.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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