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Jobsite Safety Management: Potential of Navigated Inspection | 现场安全管理：如何引导高效的安全检查

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Abstract | 摘要

Unsafe behaviors are one of the most critical leading indicators of construction accidents; therefore, timely identification of unsafe behaviors, and understanding the rationale behind them, facilitate rectification, which mitigates the probability of accidents. Unfortunately, current inspection practices are heavily experience-driven and, thus, considered systematically vulnerable. In this study, a process-oriented inspection checklist is proposed for navigation purposes. An experiment was designed and conducted to validate this proposal. The results of this experiment purported that this navigation tool enhances selective attention on pre-determined critical risks without sacrificing overall inspection performance. Although preliminary results looks promising, it is believed that network strategies should be utilized to identify critical risks with regard to spacial-temporal characteristics, facilitating optimization of inspection strategies.

Keywords: Behavior-Based Safety, Cognitive Phsychology, Construction

不安全行为是导致施工事故最主要的原因之一；因此及时识别不安全行为，理解其发生机理，矫正不安全行为，能够降低事故发生的概率。但是，目前的施工现场安全检查大都依赖于经验的多寡，而缺乏系统性的考量。本研究针对系统性的检查导航目的提出一个基于过程的检查表，并且设计相应的实验来验证检查表的可靠性。实验结果表明检查人员对导航工具中提出的关键检查项内容的选择性注意得到了加强，并且对于其余项的检查绩效没有受到损失。尽管初步结果显示检查表的可靠性，但是关键检查项的识别需要进一步适用网络分析方法，充分考虑到时空特征，便于检查策略的优化。

关键词：行为安全、认知心理、施工

Background

Construction has long been considered one of the most dangerous industries globally. In the U.S., there are 6–10 accidents that occur on jobsites every day (Lucker 1996). According to statistics from the U.S. Bureau of Labor Statistics in 2013, accidents in construction led to 828 deaths, which ranked first place among all industries. These accidents also resulted in great direct and indirect economic loss, which accounted for 8% of total costs of construction projects (BLS 2013). In the U.K., workers in construction only took up 5% of the employment nationwide, but accounted for 31% of work-related casualties. Given the severe situation of construction safety, a variety of risk-controlling methods have been taken to lower the rate of fatal accidents and minimize both casualties and economic loss. Although safety performance has improved over the past decade (as shown in Figure 1), it reached a plateau after 2010. Therefore, zero accidents in construction requires a breakthrough (Figure 1).

背景

建筑业一直被认为是全球最危险的行业之一。在美国，每天就有6–10起现场事故发生。美国劳工统计局统计数据表明2013年施工事故导致828人死亡，这个数字在各行业中排名第一。这些事故还造成了巨大的直接和间接经济损失，占工程项目总成本的8%。在英国，建筑施工工人只占全国5%的就业，但其占全国工伤事故的31%。鉴于施工安全的严峻形势，人们采取各种风险控制措施，以求降低事故发生率，减少人员伤亡和经济损失。虽然避免安全事故发生在过去十年中有所改善（如图1所示），但它在2010年之后遇到瓶颈，事故发生率下降很缓慢。因此，要做到施工零事故，就要突破现在的瓶颈（图1）。

不安全行为是事故的关键原因

大量的统计分析表明，施工现场事故与人，材料和环境密切相关。海因里希因果链理论揭示了从遗传和社会因素到伤亡发生的五个步骤，其中人的不安全行为和不安全状态是核心环节，也是比其他环节如遗传和社会环境等更容易受到人

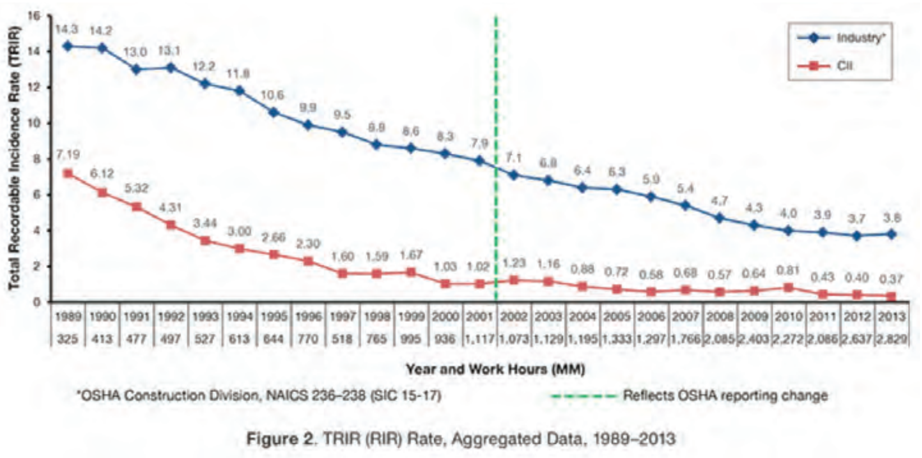

Figure 1. TRIR (RIR) Rate, Aggregated Data, 1989–2013 (CII 2014) (Source: Tsinghua University)
图1. 总事故率（TRIR）,1989–2013（CII2014）集成数据（来源：清华大学）

Unsafe Behavior is the Key to Accidents

A mass of statistical analysis shows that workplace accidents are closely related to human errors, materials, and environmental hazards (Chi et al. 2013). Heinrich's (1941) causal chain theory reveals five steps from heredity and social factors towards injuries and deaths, among which the unsafe behavior of people and unsafe state of objects is the core link and is more susceptible to human intervention than other links, like heredity and social environment. Haslam et al. (2005) thoroughly analyzed 100 diverse casualty accidents which involve different construction stages. After analyzing five hundred pieces of construction accident records offered by the British Safety and Health Executive, Suraji et al. (2001) find that 88% of accidents are related to workers' irregular operations. Analysis on the causes of construction safety-related accidents by these theories and studies show that as a direct operator in construction activities, a worker's unsafe behavior is the most direct factor in the cause of an accident (as shown in Figure 2) (Mitropoulos et al. 2005). In addition, Liao et al. (2016) asserted that unsafe behaviors result from improper environment settings. Therefore, detection of unsafe behaviors and improper environmental settings is considered the most effective and direct approach to mitigate the probability of safety-related accidents (Figure 2).

Knowledge and Practical Gaps of Inspection

Inspection of environmental settings and unsafe behaviors is the first step to risk mitigation in the construction industry. Nonetheless, operational states change dynamically in construction projects, which make behaviors hard to observe. According to statistics of the OTIS Fatality Prevention Audit (FPA) program, percentage of detected unsafe behaviors is significantly lower than environmental settings across various areas in China. Interpretation goes that hazardous environmental settings can be more easily detected than behaviors since they are relatively steady; on the other hand, human behaviors change occasionally, and thus are difficult to observe.

Current practices of inspection heavily rely on the principle of quality control (i.e., setting up control points in the project and investigating according to a risk checklist). In addition, although rules of inspections were proposed, safety inspections are heavily experience-driven. This means unsafe behaviors can be detected only if the occurrence is in the presence of an inspector. Provided risks are spatial-temporally associated, a navigation tool should improve inspection performance accordingly.

Now that most of the current safety inspections intend to inspect in an arbitrary

为干预的环节。其他研究者也有类似发现，Haslam（2005）等对类型各异、涉及建设工程不同阶段的100起伤亡事故进行了深入分析，Suraji（2001）等在分析了英国安全与健康执行局提供的500份工程事故记录，都发现88%的事故都与工人违规操作有关。以上理论和事实研究对建筑施工安全事故的致因分析结果显示，作为施工活动的直接操作者，建筑工人的不安全的违规行为是导致安全事故发生的最直接因素（如图2所示）（Mitropoulos et al. 2005）。此外，廖彬超等的研究认为人的不安全的违规行为是来自环境的不合理设置。因此，减少和防止事故发生最直接有效的途径就是通过严格的安全管理手段减少和消除人的不安全行为（图2）。

安全检查理论与实际的差别

环境设置和不安全的行为的检查是排除风险的第一步。然而，建设项目中动态变化的操作状态使得行为因素很难观察到。根据奥的斯事故预防审计（FPA）程序的统计数据，中国各地区中检查到的不安全行为的比例明显低于环境设置的检查。原因是危险环境的设置比行为更容易地检测到，因为它们是相对稳定的，另一方面，人类行为的变化突然，从而难以观察。

安全检查是施工中最常见的风险检测手段，但目前的做法过于依赖质量控制的原则（即在项目中设置控制点并根据风险清单调查）。此外，虽然提出了一系列检查规则，安全检查主要是经验驱动。这意味着不安全的行为只有在检查人员在现场检查过程中才可以被发现。既然风险是与特定时间相关的，应该提出一个检查导航工具来相应地提高检查性能。

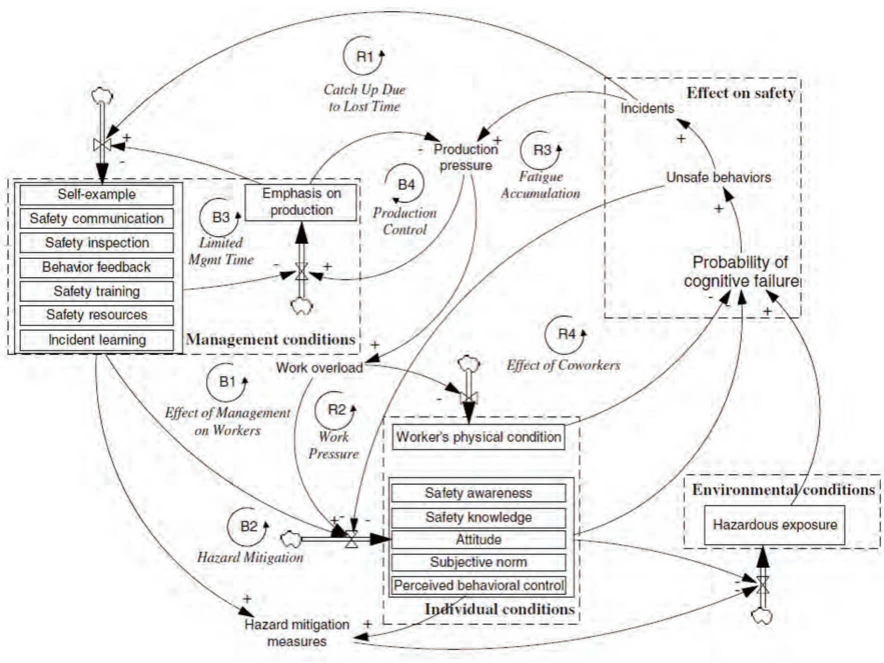

Figure 2. System dynamics of accident (Source: Tsinghua University)
图2. 事故的系统动因（来源：清华大学）

local space, in some time, inspectors would make mistakes and miss some safety risks during their observation due to the limitation of time and attention, impairing the effect of the safety inspection. First, Atkinson (1998) thought that the mission of identifying patent risks is one of the main factors causing construction safety-related accidents. Saha's (2002) simulated experiments of safety inspections on concrete column supported this argument: the quality risk recognition rate of inspectors even with the most abundant experience, possessing 10-year working experience, is lower than 80 percent. Duffuaa et al. (2015) suggested that the factors leading to observation missions should include the characteristics of the inspected object, inspection approaches and tools, and the inspector's capacity, etc. The existence of these factors would inevitably trigger inspection errors (risk mission). In addition, there are often some indistinct expressions in the risk list for inspection, increasing inspectors' actual workload (Lind 2009). Inspectors are required to consider different projects during practical safety inspections, or even to demand the worker to rectify issues on the spot, which highlights the deficiency of inspection time and the huge amount of workload (Woodcock 2014). Despite the overload of inspection tasks, the enterprise manager's universal lack of awareness in risk association also leads to insufficient safety inspection strategies and routes. Therefore, inspectors could select their route to check randomly, according to their own habit and the site composition, increasing the observation mission probability (Marlow et al. 2012).

Therefore, Woodcock (2014) proposed a rule-based inspection pattern for inspectors' thoughts and judgments, which enable different inspectors to reach appropriate outcomes under different circumstances depending on their individual preferences and knowledge. However, such a model is still in the theoretical stage and it needs a lot of practice to improve and promote use.

Solutions: Revised FPA

A process-oriented inspection checklist was proposed as a navigation tool, intended to revise current FPA program in OTIS (as shown in Figure 3 and Figure 4). The check items (risks) were mapped with standard installation steps according to the installation manual and safety standards. Senior inspectors were interviewed and this tool was cross-validated with top management.

Why Short-List?

The high division of labor in construction production and frequent alternate operation leads to a high degree of location variety of the occurrence of safety risks (Trucco and Ward 2011). On the other hand, the environment and construction workers change as the construction project progresses, which leads to a high degree of time variety (Xenidis and Gkoumas 2014).

Different from quality risk management in the manufacturing industry, the mechanism of safety risk management in the construction industry has to be process-oriented rather than results-oriented, based on the two characters above. The safety checklist is the risk list based on the inspectors' own experience, or their colleagues' in the same company or area, to prevent probable observation errors that inspectors would make in the inspection site. However, to ensure the checklist is comprehensive enough, the list is always overly lengthy. Therefore, most of the inspectors would rather use the checklist as a content prompt before checking, and a tool to examine after the entire observation, than referring to it item by item during their inspection.

The research by Woodcock (2014) showed that safety inspectors needed resources to judge whether scene features were consistent with the standard features of safety inspection. A mental model should be established before security inspection, but most of the safety inspection training mainly introduced important checkpoints, belonging to one-sided sporadic introduction. Meanwhile, his findings confirmed what Yangju Ren (2014) had proposed that safety inspectors consumed the most resources in the confirmation phase. Similarly, Seokho (2014) indicated that there should be a strong correlation between risks and the state of the operation. He proposed an activity-based inspection template that connected the security risk checkpoints with real-time operation and opened the security check mode based on the project. In theory, by using real-time safety tips, inspectors can reduce acquisition of interference stimuli (unrelated to construction status), and increase the probability of capturing the most relevant security risks associated with the current state of construction. Hamzic (2013) proposed that checking certain types selectively, based on the classification result, can reduce inspectors' workload and increase inspection efficiency and accuracy in his study

既然多数现行安全检查是在某时间区段内在任意局部空间进行安全排查，检查人员容易因时间与注意力等限制而发生错过观察安全风险而造成遗漏，削弱了安全检查效果。首先，Atkinson（1998）认为错过观察潜在的风险是诱发建设工程安全事故的主要原因之一。Saha（2002）对混凝土柱的安全检查模拟实验结果也证明了这个论点：即使是经验最丰富的检查人员（从业经历10年以上），在实验中的质量风险识别率也不超过80%。对于造成错过观察的原因，Hamzic（2013）与Duffuaa（2015）主张应包含检查对象的特征、检查方式和工具、检查员自身能力等。这些因素的存在不可避免地会触发检查失误（遗漏风险）。更为严重的是，检查人员所使用的风险清单还时常存在表意上的模糊，进一步增加了检查人员的实际工作量。实践中的安全检查还须兼顾不同项目，甚至要求当场整改，更凸显了检查工作时间不足、工作量大的问题14。并且除了超负荷的检查工作量之外，由于当前企业管理者普遍对风险关联性认识不足，故而缺乏针对性的安全排查策略和路线。因此，检查人员在实践中只能依据个人检查习惯和工地现场的布局来选择路线进行随机抽检，这更增加了其发生错过观察的概率（Marlow et al. 2012）。

因此，Woodcock（2014）为检查人员的思考和判断提供一个规则检查模式，使不同的人员在不同的情况下根据自己的个人经验和专业知识得到恰当的结果。然而，这样的模型仍处于理论阶段，需要大量的实践来改进和推广使用。

解决方案：修订FPA

面向过程全过程专项的检查清单作为导航工具来修订奥的斯目前的FPA的程序（如图3和图4所示）。根据安装手册和安全标准将检查项目（风险）与标准安装步骤映射。这个工具通过了资深检查人员进行了采访讨论，以及和管理层的交叉验证。

为什么使用短清单?

建筑业的生产过程分工高度专项化，不同的工作空间内存在频繁的交叉作业，故安全风险的发生具有高度位变性。另一方面，建设工程项目生产过程中环境与施工人员随着项目的推进不断改变，因而安全风险也具有高度的时变性。

基于以上两个特点，与制造业的质量风险管理不同，建筑业安全风险管理的机制必须是过程导向而非结果导向。

安全检查表是检查者自己或其所在单位/行业的同事基于过往经验的积累而制定出的

of quality inspection in the manufacturing industry (Figures 3 & 4).

Generally, safety inspection is an important approach to take precautions against risk and reduce accidents in engineering. However, the statistics on accident occurrences indicate that the performance of safety inspections remains to be improved. Consequently, this study will try to explore the mechanism of safety inspection. As inspectors mainly use visual searches to find hazards, the current focus will be on the most important process in the cognitive process of a visual search using cognitive psychology theory. Understanding the mechanism of this cognitive process, practical methods will be provided to improve inspection accuracy.

风险清单，它的存在原本就是为了弥补检查者在现场检查时可能发生的观察失误。然而，为了保证覆盖范围足够全面，这一风险清单往往过于冗长。因此，绝大部分检查者在使用这一清单时，更倾向于将其作为工作前的检查内容提示，以及整体观察后查缺补漏的工具，而不是在检查过程中逐条对照。

Woodcock（2014）的研究表明安全人员需要资源来判断场景特征与安全检查标准特征是否一致。在安全检查前应建立一个心理模型，但大多数的安全检查培训主要只是片面、零星地介绍重要的检查点。同时，他的研究结果证实了任衍具（2014）提出的安全检查人员在确认阶段消耗了绝大部分的资源。

同样，seokho（2014）表明风险和操作状态之间应该有强相关性。他提出了一种基于活动的检查模板，在项目的基础上通过实时操作和安全检查模式的打开连接安全风险检查点。在理论上，通过使用实时的安全提示，可以减少对检查人员干扰刺激（无关的建设状态），并增加其捕获与当前建设状态最相关的安全风险的概率。Hamzic在研究制造业的产品质量检查时提出基于分类结果选择性地检查某些需要优先关注的类别，就可以大大减少检查员的工作量，提高检查效率和准确率 。

综上所述，安全检查是防范风险和减少工程事故的重要手段。然而，事故发生的统计数据表明，安全检查的性能仍有待改进。因此，这项研究将尝试探索的安全检查机制。由于检查人员主要使用视觉搜索来寻找危险，当前的焦点是使用认知心理学理论理解视觉搜索中的最重要认知过程的机制，并提供实用的方法，以提高检查的准确性（图3、4）。

Client Site where task I performed : ____________ Name: ____________ Date: ____________

INSPECTION ON HAZARDS ACCORDING TO THE ORIENTATION *(on the Left page)*

No.	Contents	Mark	No.	Contents	Mark
C-01	Employee was not able to demonstrate lockout/tag-out procedures		D-01	Out-of-date or no inspection of lifting apparatus	
C-02	Employee did not have padlock in his/her possession during work activities		D-02	Slings not protected against sharp edges	
C-03	Equipment not equipped with lockout capability & alternative method not used		D-03	Slings bent at too sharp an angle	
C-04	Multiple employees using only one lock		D-04	Slings do not have sufficient strength for the load	
C-05	Multiple employees have keys/combinations to all locks		D-05	Knots tied in slings	
C-06	Mechanics working on de-energized equipment that has not been locked & tagged		D-06	Failure to use pre-fabricated slings (slings made up using clips)	
C-07	Inadequate electrical protection in proximity of work activity		D-07	Damaged slings not removed from service	
C-08	Use of metal ladders where there is a potential for contact with electrical circuits		D-08	Working under suspended load	
C-09	Failure to use Ground Fault Circuit Interrupters or equivalent protective devices		D-10	No certificates/inspection records to assure scaffold conforms to recognized standards	
C-10	Mechanic did not verify a "zero energy state" (power, signal, fan & lights)		D-11	Scaffolding not securely braced against swaying or movement	
C-11	Mechanic did not verify that the voltage tester was working properly		D-12	Improper structural bracing on scaffolds	
C-12	Employees working in wet pit with power on		D-13	Improper working platforms on scaffold structure	
C-13	Jewelry and other metallic objects worn around live equipment		D-14	Improper means of access and egress	
C-14	Use of uninsulated tools around live equipment		D-15	Inadequate overhead protection	
C-15	Employee does not stand to side when turning main power on and off		D-16	Improper Guardrail System	
C-17	Failure to use 2 independent means of protection to secure the car		D-18	Failure to use audio-visual alarms on false cars or running platforms	
C-18	Re-roping - Failure to use 2 independent means of protection to secure the car, activate safeties and removal of more than 1/2 the running ropes		D-19	Improper construction of false car	
C-19	Failure to use or improper use of a pipe stand or other means for landing a hydraulic elevator for work in the pit		D-20	Failure to inspect and maintain false car in good working condition	
C-20	CWT support not load rated or secured in place during repair activities		D-21	Improper activation, construction and functioning of safeties	
C-21	Employee didn`t know the weight of the car or CWT and where to locate this info		D-22	False car erected by untrained personnel w/o use of instructional guidelines	
C-22	Working closely to unguarded drive or diverter sheaves or other rotating equipment		D-23	Inadequate guard rails	
C-23	Failure to provide overhead protection while working in the hoistway		D-24	Lack of automatically activated redundant safety mechanisms to prevent failure of false car or running platform	
C-24	Unsecured rope terminations (e.g. lock wire, cotter pins)		D-25	Employees not familiar with false car construction requirements	
C-25	Unsafe oxygen-acetylene or compressed gases welding, cutting, heating equipment or procedures		D-27	Use of unauthorized jumpers (on site, on person, in tool box, etc.)	
C-26	Storage of jobsite materials creating an unsafe mechanical energy source		D-28	Non-retractable shunts used in swing or manual door locks	
C-27	Failure to use two independent methods of preventing Step Chain movement when working in the truss of an Escalator, Travolator or Moving Walk		D-29	Jumpers in place when mechanic departed jobsite	
C-28	Work procedure involves walking on step axle of escalator, travolator or moving walk		D-30	Mechanics could not explain use of jumpers	
C-29	Work procedure involves riding the escalator, travolator or moving walk with one or more of the steps or pallets removed.		D-31	No registration or control method for jumpers	
C-30	Unprotected use of hazardous chemicals, or chemicals for which the hazards and protection requirements are not known (no MSDS, etc.)		D-32	Elevator not put on inspection prior to installing jumpers	
E-01	lanyard not used or worn-out		E-08	Welding without working permit	
E-02	Safety shoes not used or worn-out		E-09	Tools put in the position near the edge of platform/car top/hoistway opening	
E-03	Helmet not used or expired		E-10	Uncovered cutout	
E-04	Safety glove not used or improperly used		E-11	Fire extinguisher not used when welding	
E-05	Welding/ drilling without protection(Protective glasses & Respirator)		E-12	Fixed supplementary lighting not used on site (hoistway)	
E-06	Failure to inspect and maintain the equipment in good working condition		E-13	Insufficient power of emergency battery	
E-07	Ladder of improper size or improperly located		E-14	Workers on site without operator certificate and work license	
			E-15	Workers not carrying proper self-locking device	

Figure 3. Short List of FPA Guidance 1 (Source: Tsinghua University)
图3. FPA短清单指南1（来源：清华大学）

INSPECTION ON HAZARDS ACCORDING TO THE ORIENTATION

A-01	Fall protection not used when exposed to a fall hazard		B-01	Improper verification of safety chain function (door, E-Stop) & Inspection Switch	
A-02	Guardrails are not adequate and no fall protection used		B-02	No Top of Car Inspection installed	
A-03	Fall protection equipment not certified or does not conform to Otis requirements		B-03	Riding the car top in Normal operation	
A-04	Inadequate barricades at hoistway openings		B-04	More than two people working in the hoistway without proper authorization	
A-05	No fall protection while working on ladder at elevations greater than 2 meters		B-05	TOCI located too far from landing and no alternate safe procedure used	
A-06	More than one person tied off to the same lifeline		B-06	Accessing /Egressing top of car with stop switch in run position	
A-07	Lifelines not protected from sharp edges		B-07	Improper verification of safety chain function (door, E-Stop)	
A-08	Inadequate or unknown capacity of anchorage point for lifeline and/or lanyard		B-08	Stop switch located too far from landing and no alternate safe procedure used	
A-09	Improper sequence of connecting and disconnecting lanyard		B-09	Improper door blocking device	
A-10	Ladder not secured at elevations greater than 2 meters		B-10	More than two people working in the hoistway without proper authorization	
A-11	Riding car top with long lanyard w/o inspection mode by 2 independent means		B-11	No pit stop switch installed	
			B-12	Mechanism (switches, ladder, releases, etc.) locations prevent use of standard procedure. No alternative safe procedure available or used	

	TICK	No.	PROCESS	RELATED HAZARDS （MUST be marked either √ or ○）
ORIENTATION			*FOR ALL PROCESSES*	*A-01~04 C-01 C-03~05 C-26 E-01~04 E-12 E-14*
		01	Hoistway Preparation	A-06~09 D-19 D-20 D-22 D-23 D-25 C-02 E-09 E-10
		02	Machine Room Completion	C-07 C-09 C-22 C-25 D-01~08 E-05 E-06 E-08 E-09 E-11
		03	Rail Installation	A-05~10 B-12 C-07~09 C-22 C-23 C-25 C-30 D-01~07 D-10~16 E-05~08 E-11
		04	CWT & Buffer Installation	A-06~09 B-04 B-10 C-07 C-09 C-21 C-22 D-01~08 D-16 D-21 E-05~09
		05	Gov & Tension Device Installation	A-06~09 E-07 E-09
		06	Carframe Installation	C-07 C-09 C-17~19 C-22 C-23 D-01~07 D-21 E-06~08
		07	Car Completion	B-11 C-17 C-18 C-19 D-08 E-07
		08	Roping	A-06~09 C-07 C-09 C-21~24 D-01~06 D-08 E-06 E-07
		09	Hoistway Equipments Installation	A-09 C-22 E-07
		10	Low Speed Installation	B-01~03 B-05 B-07~09 B-11 C-06 C-07 C-09~11 C-13~15 C-22 C-25 D-08 D-18 D-27 D-29 D-30 D-31 D-32 E-06~08
		11	Hoistway Completion	B-01~03 B-05 B-07~09 B-11 C-06 C-07 C-09~11 C-13~15 C-22 C-25 D-08 D-18 D-27 D-29 D-30 D-31 D-32 E-06~08

CONFIRM THAT ALL THE RELATED HAZARDS HAVE BE CHECKED

ASK YOURSELF

ESSENTIAL QUESTIONS	ANSWER
✧ If an unsafe behavior of worker is detected, I tend to take measures as followed *(Multiple choices)*	☐Warn orally ☐Criticize & Rectify ☐Record & Rectify ☐Punish & Rectify ☐Have clear rules on financial punishment
✧ I find it difficult to detect & record unsafe behaviors than the other hazards	☐Totally agree ☐Agree ☐Neutral ☐Disagree ☐Totally disagree
✧ Foremen evade the problems detected, and brush me off during the inspection	☐Yes ☐No

Figure 4. Short List of FPA Guidance 2 (Source: Tsinghua University)
图4. FPA短清单指南2（来源：清华大学）

导航工具的验证

在施工检查员的模拟实验中，受试者的工作年龄越高，对潜在风险的检出率越高。然而，即使那些有超过十年的经验，也最多只能找出的所有内在风险的80%，这意味着检查人员在视觉观察中漏掉了多达20%以上的安全风险。因此，风险漏检对于安全检查风险控制的可靠性非常重要，因此研究人员和施工企业需要更多的关注。

认知心理学认为人的行为是认知的直接产物，它将认知过程分为几个阶段。经验和理论都表明发现信息是安全检查最关键的阶段。如果改善安全隐患的识别率，就可以从根本上防止不安全行为的发生。如前所述，检查人员使用视觉搜索识别风险27，因此，本研究从视觉搜索和其他相关的理论对提高安全检查的性能可能解决方案进行讨论。

关于场景和场景感知的研究认为视觉搜索需要一个非常复杂的系统的注意选择系统。由于有限的时间和空间，检查人员必须在施工现场的大量信息中选择有限的信息，以确保有效地利用有限的认知资源，这被称为选择性关注。在这种情况下，如果可以指导检查人员注意到现场最重要的事情，他们的失误可以减少。以下内容将讨论如何实现这一设想。

选择性注意系统的注意捕捉包含2个阶段：早期自下而上的特征刺激凸显的阶段，和晚期的自上而下的认知控制阶段。前者强调注意力的捕获效应，后者强调的是抑制效应。在选择性注意的影响因素中，工作记忆是最重要的因素。工作记忆是一种由短时记忆形成的连续系统。它可以直接影响在安全检查的视觉搜索中的选择性注意。接下来，将讨论如何通过工作记忆引导选择性注意。

Validation for the Proposed Navigation Tool

As revealed in a simulation experiment on construction inspectors, subjects with higher working age tended to have higher detection rate of potential risks. Nevertheless, even those with over ten years` experience could hardly identify 80% of all the inherent risks within the test, which means there were up to 20% of risks missed by inspectors in the visual observation. Thus, missing risks is much more serious to the reliability of a safety inspection for risk controlling and, therefore, requires more attention from both researchers and construction companies.

Cognitive Psychology believes that human behavior is a direct product of cognitive processes. It divides the cognitive process into several stages. Experience and theories show us that discovering information is the most critical stage for inspection. If identification rate of safety hazards can be improved, unsafe behaviors can be radically prevented from occurring. As mentioned before, inspectors use visual search to identify hazards. Therefore, probable solutions to improve the performance of safety inspection will be discussed from the angle of visual search and other related theories.

Some researches in Scene and Scene Perception consider that visual search requires an extremely complicated attention selecting system (Howard et al, 2011). Due to finite time and space, inspectors have to select limited information among a tremendous amount of information at the construction site to ensure that the limited cognitive resources are utilized efficiently. This is called selective attention. In this case, if inspectors can be given some guidance to notice the most critical things at the site, their misses can be reduced. The following is a discussion of how this can be achieved.

There are two stages in the attentional capture of the Selective Attention System: bottom-up salient feature stimuli as the early period, and top-down cognitive control as the late. The former emphasizes the Capture Effect of attention while the latter emphasizes the Inhibitory Effect. Among the several influencing factors of selective attention, working memory is the most important (Awh et al. 2006). Working memory is a continuous system formed by short memory. It can guide selective attention in safety inspection directly. Additionally, it is an important factor to influence the performance of visual searches (Horowitz and Wolfe 1998). Next, it will be discussed how working memory guides selective attention.

Scholars think that working memory can affect both the early and late period of selective attention. There are two representative theories to separately interpret the bottom-up and the top-down pattern. The Bias Competition Model (BCM) considers that the "visual search template," which is stored in working memory, activates the representation of an object in long memory. This creates a competitive edge for the target object, helping to restrain the irrelevant objects when searching for the relevant ones. This is one of the bottom-up theories. A counterpart theory is the Theory of Visual Attention (TVA) (Olivers et al. 2011; Han and Kim 2009). According to this theory, different characters are given different attention weights, and weights of non-target characters are very low or even zero. This theory emphasizes that attention distribution is not mechanically decided by working memory but can be adjusted by the person. The dispute of the effect of working memory on selective attention can be explained by the differences of their experimental design. If working memory is consistent with target preference, BCM can be achieved. If not, TVA can be achieved. In this paper, it is expected that the capture effect of attention will be strengthened, so the given working memory is consistent with target preference in our research. In addition, unlimited time will be offered to participants. In this condition, working memory can affect both periods (Carlisle and Woodman 2011).

In addition, recent research has found that short-term working memory can capture attention automatically, while long-term memory may not. In this experiment, proficient participants can store situational awareness with the help of long-term memory, while novices can just use short-term working memory. So it can be inferred that experience will also affect the result of our working memory guidance.

The experiment is based on the Eye Tracker tool (as shown in Figure 5) to verify the answer to these two questions:

- Will experience influence the selective attention to on-site safety risks?
- While strengthening the short-term working memory, will selective attention of different participants with different experience be enhanced in the same way (Figures 5)?

The superiority of Eye Tracker for studies in cognition and behavior lead us to choose it in our experiment. In the area of product design, road traffic, medical practice, and crime-detection, eye movement indices can

工作记忆作为任务执行过程中暂时存储和加工信息的有限系统，能够对安全检查中的选择性注意有直接的引导作用。最具代表性的两派理论分别是偏向竞争模型和视觉注意理论。偏向竞争模型（BCM）认为注意模板是由工作记忆保持的，巩固在记忆的内容自动获得自上而下的注意偏好。这个理论强调注意模板的保持是通过对工作记忆内容的持续注意来实现的，工作记忆内容也是注意模板，因此会捕获注意。然而，视觉注意理论（TVA）认为刺激对注意力吸引是灵活的，注意并非总是指向工作记忆内容的，认知控制自上而下地给予不同刺激以不同的权重。当记忆保持了目标特征时，记忆内容就是注意模板，被赋予极高的权重；当记忆保持了目标和非目标特征，只有目标特征会获得较大的注意权重值。

对于以上各种理论争议的可能解释是，研究者们选择研究的刺激属性的差异，工作记忆内容激活水平的差异，以及每个实验认知荷载的差异。如果工作记忆与目标偏好一致，偏向竞争模型（BCM）可以被证实；如果不一致，视觉注意理论TVA被证实。本研究需要加强注意力的捕获，所以给定的工作记忆与搜索目标应当是一致的。此外，参与者没有时间限制的情况下可以保证认知负荷的充足，在这种情况下，工作记忆可以同时影响自下而上和自上而下这两个时期。

此外，最近的研究发现，短期工作记忆可以自动捕捉到关注点，而长期记忆无法做到。熟练的检查者主要在长期记忆的帮助下存储情景意识，而新手主要使用短时工作记忆。因此，长期记忆，或说经验，也会影响我们的工作记忆指导的结果。

本实验适用头戴式眼动仪（如图5所示）来测量一下两个问题的结果：

- 经验会不会影响被测试者对施工现场安全风险的选择性注意？
- 当给予短时工作记忆时，不同经验被测试者的选择性注意会不会以相同的方式被加强（图5）？

Figure 5. Eye movement tracker (Source: Tsinghua University)
图5. 头戴式眼动仪（来源：清华大学）

Figure 6. KPI (key performance index) of AOI area (Source: Tsinghua University)
图6. AOI区域的关键运行指标（来源：清华大学）

detect the area of interest during participants' observation, reflecting participants' factors of discrimination and information processing mode (Figure 6). If combined with other experiment indices, products' usability evaluation as well as behavior rationality evaluation can be obtained.

The core working memory content is four items according to previous research, which has reached the cognitive load limit of human beings. These four items are all from the fourth procedure of Buffer Installation according to the risk sorting of the items (the risk order = occurrence probability * consequence severity).

The purpose of the experiment is as follows: first, to examine whether there are differences between subjects with different experiences in their selective attention when faced with a batch of the same scene images; second, to determine if inspectors' selective attention can be improved by strengthening memory of the critical risk-items, and if the improvement is equally significant for inspectors with different experiences.

Thus, the two corresponding assumptions are as follows:

- Inspectors with more experience will find the target area in a faster way, namely, the experienced inspectors have better selective attention ability than the less experienced.
- Strengthening the working memory will quicken the speed of target finding and interest information extraction (which is the core selective attention ability) for both experienced and less experienced inspectors, while in different aspects.

Experiment Design

The subjects are 30 safety officers, inspectors, debuggers and maintenance men from a mechanical installation company. SM Headset Eye Tracker, a software of I-View, Bagaze, which can analyze the fixation attributes and area of interest (AOI) attributes (as seen in Figure 7), and SPSS, PowerPoint files for practice and formal test, PowerPoint files of FPA for both experimental and control group, and PowerPoint files for experimental group to strengthen their memory were used.

In this experiment, the pictures will be shown on a 19-inch laptop, and directions will be given to the subjects in words and recordings. There will be only one subject in each room, and three rooms are available at the same time. For the experimental group, they will have 10 minutes to look at all 90 check items, then five minutes to get familiar with the four critical items. They are called "subjects with memory." "Subjects without memory" will take all 15 minutes to look at the 90 items. Experience value is determined by subjects' working years and degree of familiarity with the FPA items. Other variables like age, educational background, and occupation are all control variables with no significant differences (Figure 7).

Procedure

Practice experiment (5 minutes) and checklist learning (15 minutes): there is a simple introduction to the experiment and practice without Eye Tracker for five minutes, followed by15 minutes to get familiar with the checklist. For the 15 minutes' checklist

本实验选择眼动仪作为记录选择性注意水平的仪器，是基于以下几点考虑：通过对眼动指标的分析可获取被试观察模式中的重点区域；眼动指标同样反映被试的因素识别和信息处理模式（图6）。眼动数据可与其他实验指标相结合，可以实现对产品的可用性评估和行为的合理性评价。

关键工作记忆内容是四个项目，根据以往的研究，四项工作记忆已经达到了人类认知的极限。这四个项目都是属于电梯导轨安装的过程中的子步骤，根据项目的风险排序（风险顺序 ＝ 发生概率 ＊ 后果严重程度），选择得分最高的四项作为实验内容。

本实验的目的是为了研究电梯安装公司的检查人员中，不同工作经验的被试在面对相同一批场景图片时的选择性注意行为有没有差异。其次，在给予与任务内容相同的短时工作记忆时，能不能提高检查人员的选择性注意，并且对于不同经验的被试这种短时工作记忆的促进作用是否同样显著。

因此，提出两个对应的假设如下：

- 经验越高的检查人员能够更快地找到目标区域，也就是说，经验越高选择性注意的能力就越高。
- 在加强与检查任务相关的工作记忆之后，检查人员能更快地找到目标区域以及提取有用信息（这些都是选择性注意的核心能力）。并且不同经验的检查人员提高的方面有所不同。

实验设计

被试选取30名奥的斯公司的安全官、监督、调试员和维修工(总体样本全部为男性，因此抽样样本也全部为男性)，实验设备是SMI头戴式眼动仪，数据录入用i-view软件(200hz)，数据分析和导出使用begaze软件（如图7所示）和spss软件。电子档实验材料包括练习实验PPT(3张照片)、正式实验PPT(24张照片)、实验对照组共用的FPA内容的PPT(90项内容)、实验组用的加强工作记忆的PPT(4个关键检查项每项2张)。纸质档实验材料有答题所用的彩打照片和FPA检查表。实验所用照片均由奥的斯公司提供（图7）。

实验流程

阶段一：练习实验(5分钟)和检查表熟悉阶段(15分钟):这个阶段为正式实验做铺垫，练习实验是为了让被试熟悉实验流程，检查表的熟悉是实验干预环节，实验组有额外工作记忆而对照组像往常在工地一样没有差别。之所以每个人都要重新过一遍

Figure 7. The fixation point with the change of time (Source: Tsinghua University)
图7. 眼动仪中注视点随时间的变化（来源：清华大学）

learning, experimental subjects will take 10 minutes to look at, listen to, and read all 90 check items, then 5 minutes to remember the four critical items, while the control group will spend the whole 15 minutes only to look at, listen to, and read all 90 check items without memory for all the items.

Formal experiment (10 min): the instruments will be calibrated, then subjects do the scene search, judge, and give an answer of no or yes.

Answering questions (20 min): the FPA list and the paper photos in which they think there are safety hazards (for which they gave answer "yes" in the previous step) will be offered. Subjects will write the number of the photos next to the corresponding checklist.

Preliminary Results

The main indicators for measuring selective attention performance are the fixation count on the picture and average fixation time on AOI (area of interest). Fixation count on the picture is the index, recording frequencies it takes the subject to lock onto the area of interest, which can tell us the efficiency of their search. Average fixation time on AOI shows the degree of difficulty for subjects to extract and process the information; the more time-consuming the search, the greater the difficulty in finding and understanding the AOI message.

The less fixation counts in the picture, the better search efficiency, as mentioned above. Fixation number of the inexperienced subjects decreased with additional experiments on working memory of four critical inspection items; the experienced, which was initially lower, showed a slight increase (as plotted in Figure 8). An analysis of variance (ANOVA), with working memory (WM) and experience as factors, was conducted on average fixation times, confirming strong effects only in WM (F=4.132, p=.043), yet no significant effects in experience (F=2.236, p=0.136), and a significant interaction between fixation counts and experience (F=6.529, p=0.011).

Thus, providing experience does not correlate significantly with fixation count, indicating experience has little impact on locking ability. However, when given additional working memory of the four critical items, search efficiency under low experience significantly increased because of the reduction of fixation count, while search under high experience showed a slight deterioration (Figure 8).

The decrease of average fixation time means that the subjects need less search time to extract the useful information after locking onto the targeted area. Average fixation time of the experienced subjects decreased with additional experiments on working memory of the four critical inspection items (as plotted in Figure 9). Additionally, the variation of average fixation time under relatively low experience was found to be considerably slight, with an intercept difference of 53 ms (26 ms under low experience; 79 ms under high experience). An analysis of variance (ANOVA), with WM and experience as factors, was conducted on average fixation time, confirming strong effects of both WM (F=9.595, p=.002), and set experience (F=9.553, p=.002), and significant interaction of the two variables (average fixation time & experience) considered simultaneously (F=376, p=.037).

Thus, the more experience, the better information extraction ability and search efficiency, which confirms the first assumption. Furthermore, when given additional working memory of the four critical items, search efficiency of the experienced subjects significantly increased because of

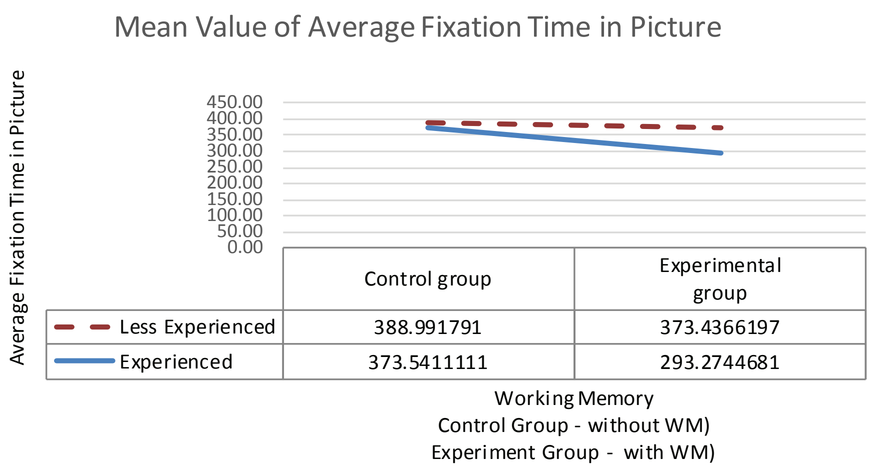

Figure 8. Mean Value of Fixation count in Picture (Source: Tsinghua University)
图8. 图片中的平均注视时间值（来源：清华大学）

FPA检查表内容，也是为了统一从不同环境下过来参与实验的每个人实验的记忆情绪状态。

阶段二：正式实验阶段(10分钟):这个阶段是数据收集阶段，所有被试的眼动信息和对题目的判断都会有答案。

阶段三：答题阶段(20分钟):答题阶段没有时间限制，被试需要尽量保证答案正确，因此，根据被试最长使用时间20分钟最为上限。

实验初步分析

不同经验的被试在场景搜索和判断阶段的选择性注意表现有显著差异，具体表现在注视次数和平均注视时间上。在整幅图中的注视次数越多，表明搜索效率越低，经验越高的被试，注视次数越少，表明他们能更快地找到目标区域，并且较少地被其他物体干扰分心。平均注视时间越低说经信息提取难度越低，数据显示经验越高的被试，平均注视时间越低，表明他们能更快地从兴趣区域找到自己有用的信息，并更快地做出判断。以上指标都显示经验高的被试，选择性注意的能力也越强，他们能更快地瞄准场景中的关键兴趣区域，进行信息的提取和判断。

如上所述图片内注视次数越少，搜索效率越高。当额外施加四项关键检查项的工作记忆时，低经验的被试注视次数的减少，高经验被试的注视次数从较低的水平略微增加（如图8所示）。方差分析（ANOVA）表明经验值的不同并不会显著影响平均注视次数（F ＝ 2.236，P ＝ 0.136），但是实验所施工作记忆的差异会对平均注视时间有显著的影响（F ＝ 4.132，P ＝0. 043），并且工作记忆差异和经验值高低之间的有显著交互作用（F ＝ 6.529，P ＝ 0.011）。

因此，经验对于被试在图片中的注视点数量没有显著影响，表明经验对兴趣区域（AOI）的锁定能力没有显著影响。然而，当给予四个关键检查项的工作记忆时，低经验被试的搜索效率显著增加（注视次数减少），而高经验被试的搜索效率反而略有下降（图8）。

在兴趣区域的每次注视所用的平均注视时间越少意味着被试在锁定目标区域后提取有效信息所用的时间更少。实验结果显示在额外给予四项关键检查项的工作记忆后，高经验被试的平均注视时间增加（如图 9所示，而低经验被试的平均注视时间显著升高，两者截距差异有105毫秒（高经验被试增加79毫秒，低经验被试减少26毫秒）。方差分析显示工作记忆(F=9.595，p=.002)和经验(F=9.553，p=.002)两个因素对平均注视次数都有显著影响，并且两

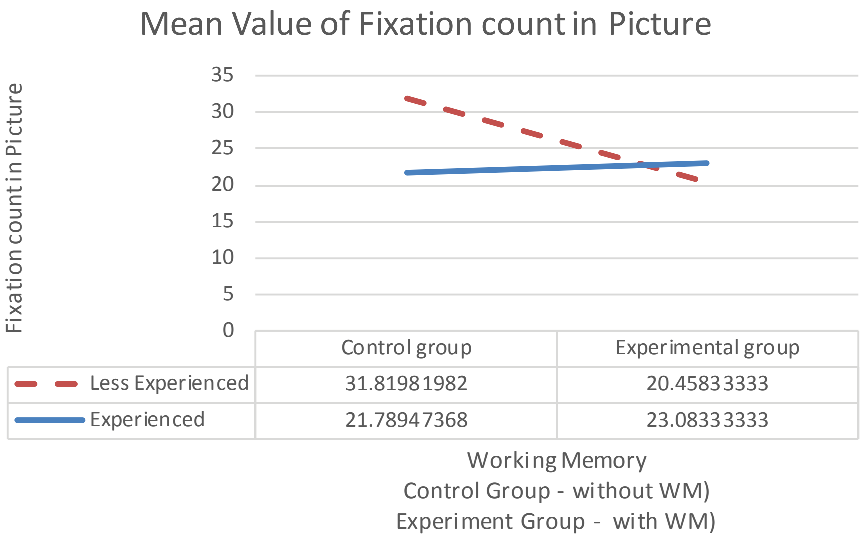

Figure 9. Mean Value of Average Fixation Time in Picture (Source: Tsinghua University)
图9. 图片中的平均注视时间值（来源：清华大学）

reduction of average fixation time, while subjects with low experience have not shown such significant improvement (Figure 9).

The above results support the assertion that maintaining critical task-related working memory load during search does impact overall search efficiency, and does produce considerable difference on inspectors who have different experience levels.

There is a significant difference between subjects with different experiences in their selective attention during the step of scene search and judgment. Experienced inspectors do have better search efficiency and ability. Meanwhile, experience and working memory have a cross-impact on fixation count, fixation times, and the post-searching stage. The decrease of fixation count and average fixation time, indicate the improvement of visual search efficiency, or rather, the selective attention efficiency. While strengthening the working memory, the search efficiency of inspectors both improved in different ways; the less experienced by enhancing the AOI locking ability, and the experienced by growing the information extraction ability. In short, strengthening the critical inspection items in working memory can help both experienced and inexperienced inspectors to better allocate the selective attention, improving inspection efficiency.

Additional Information

Most of the studies assume the risks take place independently. However, theories have argued against such an assumption. Future studies should prioritize risks, assuming their associations to derive legitimate inspection rules. It is believed that network techniques facilitate visualization and exploration of dependent characteristics of risks and, therefore, risks can be prioritized and inspected with their spatial-temporal characteristics.

The mechanism of how environment and design influence the behavior remains unclear. Knowing how the working condition creates the demand of workers adjusts their behavior system by stimulating the way they think about demand. Although the construction industry research tries to explain people's unsafe behavior, the existing model for human and environment interaction effects is not detailed enough. It is recommended that human reliability analysis (HRA) is employed to understand of the influence of unstructured environment on unsafe behaviors and proposed design strategies that mitigate jobsite unsafe behaviors.

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个因素对平均注视次数有显著的交叉作用(F=376，p=.037)。

因此，经验越多，选择性注意能力中的信息提取能力就更高，这证实了第一个假设。并且当给予额外的四项关键检查项的工作记忆时，高经验被试的搜索效率由于平均注视时间的减少而提升，低经验被试的平均注视时间没有显著变化（图9）。

同时，经验和工作记忆对注视次数、注视时间和后搜索阶段时间都有显著交叉影响。注视次数，平均注视时间和后阶段的持续时间的减少都表明视觉搜索效率的提升，即选择性注意能力的提升。加强工作记忆能通过不同的方式提高不同被试的搜索效率。低经验被试锁定安全隐患的所需注视次数更少，高经验被试提取场景信息所需的平均注视时间更短。低经验被试的搜索阶段时间显著减少，表明处理和判断信息的时间减少。总之，加强关键检查项的工作记忆，可以帮助检查人员更有效率地找到安全隐患，其中低经验的检查人员话更少的次数在图片搜索上，而高经验的检查人员每次注视花更少的时间来判断出是否有隐患。

未来研究方向

大多数研究假设风险的发生是相互独立，但这样的假设在理论上是站不住脚的。未来的研究应优先考虑风险，在假设它们之间相互联系的基础上得出合理的检查规则。网络技术可以促进关于风险独立特征的可视化探索，因此，可以根据风险的时空特征排序进行优先检查。

环境和设计影响行为的机理尚不清楚。需要了解工作条件如何创造工人需求，并通过激励他们对需求的思考方式来调整他们的行为系统。虽然建筑业的研究试图解释人们的不安全行为，但现有的模型对人类和环境的相互作用效果不够详细。建议使用人因可靠性分析（HRA）来理解非结构化环境对不安全行为和已有设计策略的影响，从而减少现场不安全行为。

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