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Limitations in the field of vision of young operators of utility all-terrain vehicles

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ABSTRACT

Problem: All-Terrain Vehicles (ATVs) cause a distressing number of fatalities and injuries among farm youth in the United States. The number of severe injuries caused by ATV crashes on farms, which stood at 25 children in 2019, is expected to rise due to increased ATV sales during the COVID-19 pandemic. Existing research into children's injuries has explored physical capabilities like anthropometry, strength, and visual acuity. Yet, studies assessing youths' physical ability to operate ATVs remain limited. This study tests the hypothesis that diminished vision field in young ATV operators raises crash risks. *Methods:* This study used SAMMIECAD digital human modeling system to simulate and compare the field of vision of youth and adult ATV operators. The simulations incorporated 3-D mockups of ATVs, humans, sprayer tanks, windshields, and obstacles. Ten utility ATVs and children of both genders across nine ages (8–16) and three height percentiles (5th, 50th, 95th) were evaluated. *Results:* Simulations showed that young ATV operators generally have a more restricted field of vision than adults, particularly those aged 6–11 years. *Discussion:* Visual limitations hinder riders' ability to see ATV controls, potentially leading to vehicle control loss. Moreover, they impair environmental perception during riding, compromising youths' ATV operation abilities and increasing crash risks. *Practical Applications:* These findings offer crucial data in support of modifying ATV safety guidelines. Additionally, they can guide youth occupational health professionals in preventing ATV-related incidents in agricultural settings.

1 Problem.

All-Terrain Vehicles (ATVs) cause a staggering number of fatalities and injuries among youth in the United States. The development of special farming attachments for utility ATVs, such as sprayers, tillers, trailers, and racks, made them a popular working machine in the agricultural setting, especially among youth (Cavallo et al., 2015; Murphy & Harshman, 2014). For instance, individuals younger than 16 are now more likely to have ridden a utility ATV than a tractor (Goldcamp et al., 2006). However, almost 3,000 youth have died, and 103,100 were hospitalized due to ATV-related crashes between 2014 and 2017 (CPSC, 2018). According to data from the 2019 National Electronic Injury Surveillance System, 15.3% of those incidents happened on farms or ranches (Wiener et al., 2022). Moreover, a survey among rural households revealed that 88% of ATV-related incidents involve youth as passengers, riders, or bystanders (Goldcamp et al., 2006).

ATVs have low-pressure tires, narrow wheelbase, and high center of gravity (Ayers et al., 2018; Chou et al., 2022; House et al., 2016). Utility ATVs and sport models (which include youth ATV models) have several design differences. Utility models have higher ground clearance, stronger torque for hauling and towing, rear and front racks for carrying loads or mounting equipment, a hitch to pull implements, and heavier weights (Khorsandi et al., 2021). Accordingly, utility ATVs are more suitable and commonly used for tasks in agricultural settings. Therefore, in this study, we define agricultural ATVs as adult-sized, utility ATVs (straddle/handlebar version) used on farms and ranches.

Youth are more vulnerable to occupational incidents than adults because of their less developed physical capabilities and psychological and behavioral characteristics (Brison et al., 2006; Hard & Myers, 2006; Hendricks et al., 2005; Khorsandi Kouhanestani et al., 2022; Marlenga et al., 2001; Pollack-Nelson et al., 2017; Reed et al., 2005; Serre et al., 2010; Towner & Mytton, 2009). For instance, previous research demonstrated that youth younger than 16 cannot reach or activate the controls of most agricultural ATVs commonly found on U.S. farms (Bernard et al., 2010; De Moura Araujo et al., 2022a; De Moura Araujo et al., 2022b). Such limitations put youth at greater risk while riding agricultural ATVs, which are primarily designed for adults (American Academy of Pediatrics, 2018; Anson et al., 2009; Dolan et al., 1989; Mattei et al., 2011; Murphy & Harshman, 2014; Scott et al., 2011; Shults

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Nomenclature

Name	Abbreviation
4-Wheel-Drive	4WD
All-terrain vehicle	ATV
American Academy of Pediatrics	AAP
American National Standards Institute	ANSI
ATV Safety Institute	ASI
Bicycle Helmet Safety Institute	BHSI
Computer-Aided Design	CAD
Cubic Capacity	cc
Department of Transportation	DOT
Digital human models	DHM
Electric Power Steering	EPS
Exposure Ratio	Er
Field of Vision	FV
National Children's Center for Rural and Agricultural Health and Safety	NCCRAHS
National Highway Traffic Safety Administration	NHTSA
Root Mean Square Error	RMSE
Seat Reference Point	SRP
Specialty Vehicle Institute of America	SVIA
Three-dimensional	3-D
U.S. Consumer Product Safety Commission	CPSC
Virtual Reality	VR

et al., 2005).

Another limitation of youth relates to their field of vision. The field of vision of an ATV operator is the visible area they can scan from their seated position in the vehicle. Many believe that youth have a reduced field of vision compared to adults due to their shorter stature and eye height while seated on an ATV (Behboudi et al., 2017; Chang et al., 2010; David et al., 1986; Huisingh et al., 2015; Whiteside, 1976). Previous studies have shown that a restriction in an operator's field of vision significantly increases the likelihood of a crash and/or loss of control, which can lead to rider and bystander injuries (Johnson & Keltner, 1983; Keltner & Johnson, 1987).

The agricultural setting presents several challenges that can potentially increase youth's likelihood of ATV crashes due to limitations in their field of vision. First, ATV safety guidelines require the use of a full-coverage helmet for occupational use (NCCRAHS, 2018), which diminishes the rider's peripheral vision by approximately 3% (Adhilakshmi et al., 2016). Second, sprayer tanks, commonly attached to the front rack of agricultural ATVs, create a physical barrier in front of the rider, hence likely reducing their field of vision. Lastly, windshields (widespread in regions with severe weather) can potentially create another visual hindrance to operators during wintertime since they get dirty and become frosted.

The ATV Safety Institute (ASI) provides a guideline to help parents evaluate their youth's visual perception (ATV Safety Institute, 2017). According to the guideline, youth should be capable of seeing, perceiving depth, having adequate peripheral vision, judging the speed of moving objects, estimating the distances of objects (by units such as feet), and following the movement of objects. In that regard, the ASI provides definitions and recommendations to examine each visual capability (ASI, 2020). For example, the ASI defines peripheral or side vision as the ability to see to the sides while looking straight ahead. According to the ASI, youth's peripheral vision should be determined by evaluating if the youth can see objects at 90° to the side while looking straight ahead (ASI, 2017). Nevertheless, the ASI's guidelines do not provide a method for quantitatively evaluating youth's field of vision, nor do they provide a threshold for a minimum acceptable field of vision for the safe operation of ATVs.

Previous studies indicate that youth's reduced field of vision potentially increases their likelihood of crashing agricultural ATVs. However, to the best of our knowledge, no available work has evaluated youth's field of vision while operating those machines. There is a need for a study to quantify youth's field of vision while riding agricultural ATVs and compare it with the visual capabilities of an adult counterpart. Furthermore, the influence of external factors such as helmet use, the presence of a sprayer tank, and windshield use on the rider's field of vision should also be evaluated.

It has been hypothesized that youth ATV operators have a narrower field of vision than adult operators. This hypothesis has been formulated based on research that showed that youth have a diminished field of vision compared to adults (Behboudi et al., 2017; David et al., 1986; Huisingh et al., 2015; Whiteside, 1976). In addition, we hypothesize that helmets, sprayer tanks, and (frosted/dirty) windshields disproportionally affect the field of vision of youth ATV operators due to their shorter height and eye position compared to their adult counterparts.

In view of our hypotheses, the present study aimed to compare the field of vision of youth and adults while operating agricultural ATVs. The field of vision of male-and-female youth of three height percentiles (5th, 50th, and 95th) and their adult counterparts (50th percentile) were evaluated in 5,040 computer simulations, considering 10 utility ATV models under different combinations of helmet, sprayer, and windshield use.

2. Methods

The quantification and evaluation of the field of vision of ATV operators was carried out in five steps. First, we collected the dimensions of various ATV models to create a three-dimensional (3-D) representation of them. Second, we designed 3-D mockups of the external factors that affect the operator's field of vision (helmet, sprayer tank, and windshield). In the third step, we identified a database containing anthropometric measures of male-and-female youth of various ages (8–16 years old) and height percentiles (5th, 50th, and 95th). This database was then used to create 3-D mockups of the ATV operators. The fourth step consisted of quantifying the field of vision of the ATV operators in a virtual environment (SAMMIE CAD – SAMMIE CAD Inc., Leics., UK), including the 3-D mockups of ATVs, humans, a sprayer tank, a windshield, and simulated obstacles. Lastly, we validated the results of the virtual simulations in field tests with actual riders and ATVs.

2.1. ATV mockups

In total, we evaluated 10 agricultural ATV models. Selected models for this study consisted of vehicles from the most common manufacturers in current use in the United States (Apollo, Arctic Cat, CF Moto, Honda, Polaris, and Yamaha). Furthermore, general descriptive variables such as manufacturer, model, series, engine capacity (cc), drive train (4WD/2WD), transmission, suspension type, presence (or not) of an electric power steering (EPS) assist system were also recorded to provide a wider context in the interpretation of the results.

An initial attempt to create 3-D ATV mockups consisted of using photogrammetry (Fathallah et al., 2009), where several pictures of a single object are taken from various angles and then processed to create a 3-D model of the object. However, initial trials were laborious, and the results were not satisfactory (low accuracy). A second attempt consisted of using a virtual reality (VR) tracking system (Vive – HTC Corporation, China). This alternative was selected because it provided fast and accurate (±1 mm) measurements.

The VR tracking device used for data collection uses a local coordinate system to record the spatial location (X, Y, Z) of a given point. A comprehensive description of installing and using the VR system to track objects' spatial coordinates can be found elsewhere (Kreylos, 2016). In summary, the system uses a set of infrared emitters (lighthouses) and receivers (photodiodes) to track the position of a handheld controller, as shown in Fig. 1. The VR system is somewhat analogous to a global positioning system (GPS), where the lighthouses represent the satellites orbiting space and the controller photodiodes represent the signal receiver. The lighthouses are placed at a distance from where the object of interest is standing. They shoot horizontal and vertical infrared laser beams that will be detected by the photodiodes, which are part of the VR controller (Fig. 1b). The controller's position and orientation are calculated by the difference in time at which each photodiode is hit by the lasers (Niehorster et al., 2017). As the user moves the controller around the object, the spatial coordinates (X, Y, Z) of the controller change accordingly. Therefore, by recording the coordinates of several vertices of the object, it is possible to develop a 3-D representation of it.

The VR tracking system was used to locate key ATV features, such as the ATV seat, handlebars, chassis, etc. Key features are features that either: (1) have a direct impact on the rider's field of vision, or (2) are used to assist in the simulation. For example, the ATV chassis represents a physical barrier located right in front of the rider; depending on its design, it can seriously affect the rider's field of vision. In contrast, the vehicle's seat and handlebars are also key features because they are used as references to place the virtual riders in the 3-D vehicle models (e.g., the rider's buttock is positioned on the seat while the rider's hands are positioned on the handlebars' handles). Each key feature was represented by a set of coordinates that contained all vertices of that feature. In total, 38 points were collected per ATV. The points were selected aiming to get an efficient representation of all ATV key features. After data filtering, the data were processed in SAMMIE CAD for a 3-D representation of the evaluated vehicle, as shown in Fig. 2.

A custom program was developed to calibrate the system, log, and manipulate data. This program was initially retrieved from Kreylos (2016) and then modified to meet the specific needs of the present study. The software runs in Linux operating systems and has several functionalities that are useful to the user. Examples of these functionalities are a 3-D grid, which allows for real-time visualization of labeled points, and a measuring tool (to verify the measurement scale).

Since the VR measurements rely on the communication between infrared emitters and receivers (photodiodes), an external source of light such as the sunlight could potentially interfere and cause errors during the data collection. Therefore, to prevent adverse effects from the sunlight, the measurements were collected inside a tent covered by a white rooftop, which reduces the interference of solar rays in the communication between the lighthouses and the photodiodes.

2.2. External factors (Helmet, sprayer Tank, and Windshield)

The external factors that can potentially influence the field of vision of an ATV operator were initially designed on SolidWorks (SolidWorks Corp., Waltham, MA, USA). Then, they were exported to SAMMIE CAD.

The helmets developed for the simulations were based on a Shoei RF-1400 full face motorcycle helmet. This helmet was selected because the ATV safety guidelines require the use of a full-coverage helmet for occupational use (NCCRAHS, 2018). In addition, this helmet meets the requirements of the National Highway Traffic Safety Administration (NHTSA), Department of Transportation (DOT) FMVSS 218 standard (National Highway Traffic Safety Administration (NHTSA) – DOT, 2015).

Since the Shoei RF-1400 is an adult-sized helmet, the helmet designed for adults was a replica of it. The other helmets were designed as scaled models of the adult-sized helmet. The Bicycle Helmet Safety Institute (BHSI) recommends helmet sizing based on the rider's head size. We retrieved youth's head size from Snyder et al. (1977) and then calculated their recommended helmet circumference size based on BHSI's sizing chart (Bicycle Helmet Safety Institute). The adult-sized helmet was then scaled by the ratio between the youth's recommended helmet circumference size and the adult's recommended helmet circumference size (Equation (1).

$$ScaleFactor = \frac{Youthrecommendedhelmetcircumferencesize}{Adultrecommendedhelmetcircumferencesize} \quad (1)$$

The sprayer tank developed for the simulations was based on a Rice-Mate™ ATV Broadcast/Levee 35-gallon sprayer tank. This model was selected since it is one of the tanks designed for utility ATVs. While we acknowledge that various sprayer tank models exist for ATVs, we had to select one to allow a consistent evaluation approach.

Lastly, the windshield developed for the simulations was based on a Polaris Lock & Ride Windshield for Ride Command. Like the sprayer tank selection, this model was selected for allowing a consistent evaluation approach.

2.3. Human mockups

Human mockups were developed in SAMMIE CAD. In total, 54 youth mockups were created, a combination of two genders, nine ages (8–16), and three height percentiles (5th, 50th, and 95th). This age range was selected because most youth start operating farm machinery at 8 years old (Marlenga et al., 2001), and most ATV-related crashes occur with riders younger than 16 years old (Denning et al., 2014). Moreover, two adult mockups (male and female of the 50th height percentile) were also created to establish a baseline for comparisons.

Digital human models (DHM) are created in SAMMIE CAD based on

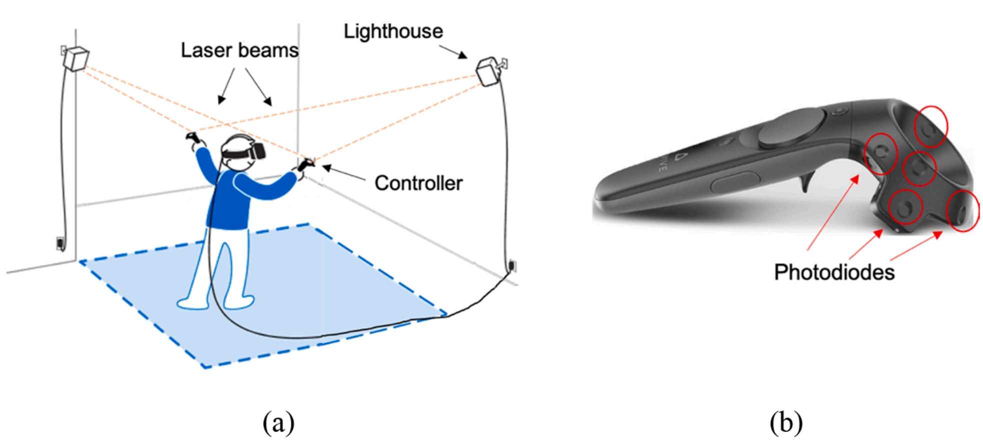

Fig. 1. (a) Vive tracking system (adapted from Seekpng), and (b) Vive tracker controller (source: HTC).

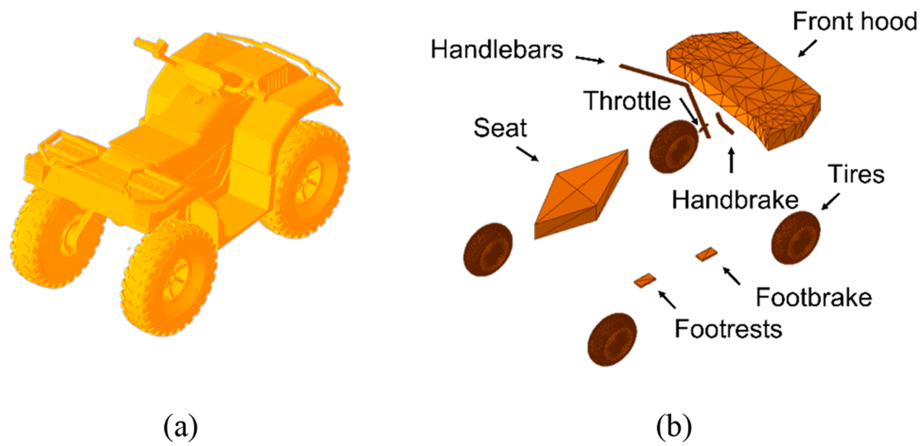

Fig. 2. 3-D representation of ATV mock-ups. (a) Fully assembled model – for visualization purposes only; (b) Example of a 3-D ATV mock-up used for the virtual simulations in SAMMIE CAD.

eight selected anthropometric data: stature, shoulder breadth, arm length, sitting height, hand length, sitting shoulder height, knee height, and buttock-knee length (Fig. 3a). The anthropometric dimensions used as input to SAMMIE CAD were retrieved from the database of Snyder et al. (1977), which includes measurements from 3,900 subjects from 2 to 18 years of age for both genders. The anthropometric measures were based on the mean values of groups of subjects with the same age, gender, and stature percentile. For example, the arm length of a 12-year-old male of the 95th body size percentile was calculated as the average arm length of all 12-year-old males that were 160.4 cm tall, which corresponds to the 95th percentile stature of 12-year-old males (Snyder et al., 1977).

One of the inputs required to create customized humans (seated shoulder height) was not available in the database. Therefore, the missing input was estimated through interpolation of the available data (Fig. 3b). Equation (2) was used to obtain an estimate of the missing parameter.

$$Seatedshoulderheight = Sittingheight - Headandnecklength \quad (2)$$

Both parameters on the right-hand side of Equation (2) were available in the database evaluated (Snyder et al., 1977).

2.4. Field of vision

In order to assess the field of vision of the subjects, virtual targets were created and placed around the ATVs. The targets consisted of vertical grids 2 m tall (spaced in 10 cm installments) spanned at 0°, 30°, 60°, 90°, 120°, 150°, and 180° with radii of 1.0, 1.5, and 2.0 m (21 targets), as shown in Fig. 4a and 4b. Further, SAMMIE CAD allows the user to position the “camera” at the virtual human’s eye point (i.e., the user can observe what the DHM sees; Fig. 4c). The field of vision of the subjects for a given ATV and riding condition (i.e., combination of helmet, sprayer tank, and windshield) was determined as the sum of the number of visible squares for each of the 21 virtual targets positioned around the ATV, as demonstrated in Equation (3).

$$FV = \sum_{r=1}^{2} \sum_{\theta=0}^{180} h_{r,\theta} \quad (3)$$

Where:

FV: Field of vision index for the subject in m;

r: Radius of the target (r = 1.0, 1.5, or 2.0 m);

θ: Angle at which the target was spanned (θ = 0°, 30°, 60°, …, 180°);

$h_{r,\theta}$: Number of visible squares of the target located at (r,θ).

The FV has a proportional relationship with the field of vision of the subjects (i.e., higher FV values indicate a greater field of vision). In comparison, smaller values of FV indicate a smaller field of vision. Since there were 21 virtual targets, FV ranged from 0 to 420.

It is important to mention that an initial investigation was conducted to optimize the potential radii range for the virtual targets. Preliminary results demonstrated that all 20 squares of any virtual target placed at a distance of 2.5 m from the ATV seat were visible for all subjects, regardless of the ATV model. Therefore, the maximum radius of 2 m was adopted for the simulations.

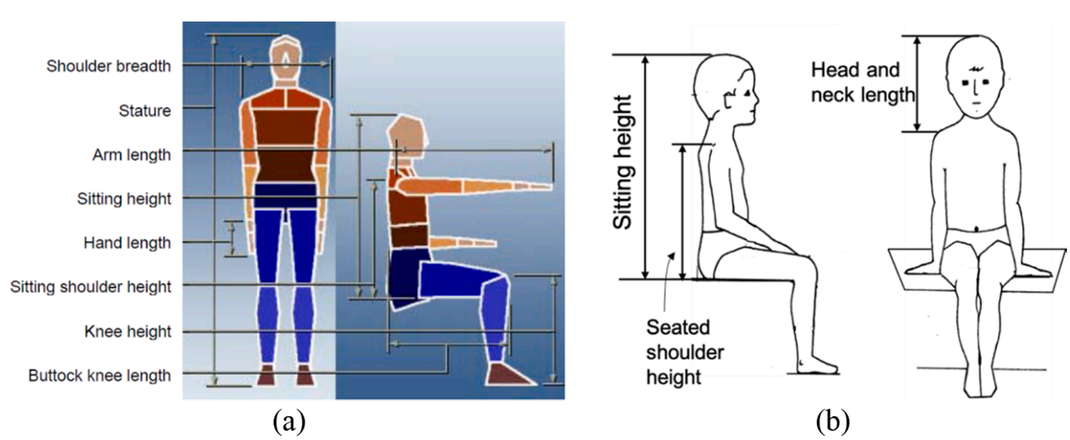

Fig. 3. SAMMIE CAD human creation. (a) Selected input variables (source: SAMMIE CAD Inc.); (b) Interpolation of missing variable (seated shoulder height) – Adapted from Snyder et al. (1977).

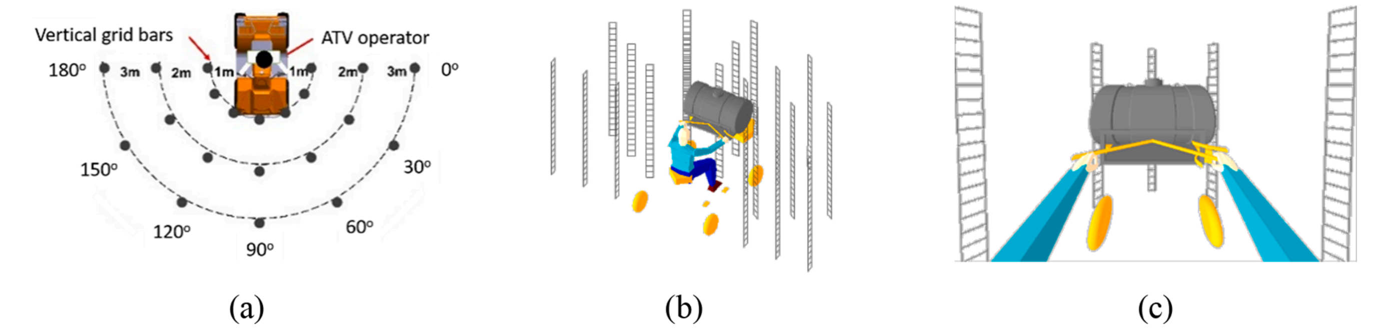

Fig. 4. Visual Fields. (a) Visual targets configuration, (b) Computer simulation (SAMMIE CAD), and (c) DHM eyepoint.

2.4.1. Quantification

While the proposed methodology allows for a logical quantification of the field of vision, it is not quite practical. Counting the number of visible squares is time consuming. For this reason, we developed a computer vision algorithm (openFV) to assist in the quantification of the field of vision of the machine operator. More information about the installation and use of this computer program is available in its online repository (De Moura Araujo, 2022). In summary, we used a screenshot software tool (Greenshot) to capture screenshots from the various scenarios created in SAMMIE CAD (combinations of rider gender, age, and height percentile, ATV model, and use of helmet, protective windshield, and sprayer tank). Each screenshot contained only half of the scene since the ATVs are symmetrical.

Then, we used openFV to process the screenshots and get an estimate of the FV (Equation (3) of each screenshot. One example is shown in Fig. 5.

While using openFV has its advantages, it can sometimes generate inaccurate results. We evaluated the performance of openFV over 504 images (1512 vertical grids). The selected images included simulations from two ATVs in three scenarios (*i*: no windshield and no sprayer tank; *ii*: windshield but no sprayer tank; and *iii*: sprayer tank but no windshield). The results indicated a mean error of 0.33 "squares" or 1.7 % per vertical grid (each grid has 20 squares). The mean error for ATVs without windshields or sprayer tanks (scenario *i*) was 2.2 %. On the other hand, the mean error for scenarios *ii* and *iii* were 1.7 % and 1.1 %, respectively. To ensure our results were 100 % accurate, we manually inspected the output of openFV (labeled images with bounding boxes for each visible square and the numeric value of FV (Fig. 5) and annotated the FV for each vertical grid on each image.

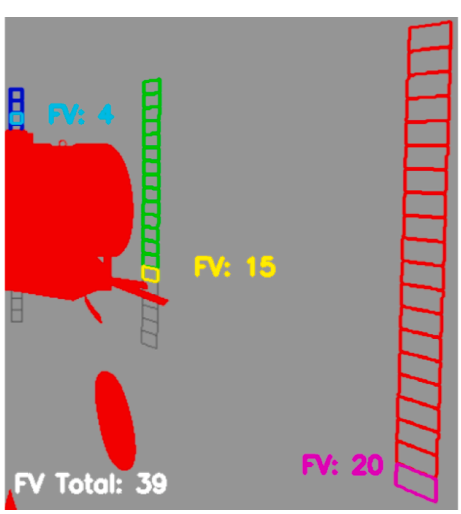

Fig. 5. Example of openFV output: bounding boxes for each visible square and the numeric value of FV for each vertical grid.

2.5. Data analysis

In order to evaluate the percent of ATVs with visual limitations to youth, we calculated the exposure ratio for each youth on each ATV (Chang et al., 2010). The exposure ratio is computed as the ratio between the FV of a young operator and the FV of their adult counterpart, as presented in Equation (4).

$$E_r = \frac{FV_y}{FV_a} \tag{4}$$

Where:

E_r: Exposure ratio;

FV_y: Field of vision index of the young operator;

FV_a: Field of vision index of the adult counterpart.

ATVs with E_r smaller than 1.0 were considered to represent a visual limitation for youth, as recommended by Chang et al. (2010).

2.5.1. Validation

In order to validate the results of the simulations, an experimental setting was built to recreate the virtual scenarios of SAMMIE CAD. Wood boards 2-m tall with a cross section of 5 × 10 cm (2 × 4 inches) were placed around ($r = 1.0, 1.5, 2.0$ m; $\theta = 0°, 30°, \ldots, 180°$) an ATV model Honda Rancher 4 × 4. The boards were marked in installments of 10 cm in accord with the virtual simulations' requirements. Two male adults were used as subjects for the validation.

The anthropometric dimensions of the subjects were measured with a measuring tape graduated in mm and then used as an input in Sammie CAD to create 3-D mockups. We then calculated the FV of the subjects in SAMMIE CAD for comparison with the field tests.

The root-mean-square error (Equation (5) between the FV measured experimentally and the FV estimated through SAMMIE CAD was used as the metric to validate the results of the virtual simulations.

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{\left(FV_{SAMMIEi} - FV_{expi}\right)^2}{n}} \tag{5}$$

Where:

RMSE: Root-mean-square error;

$FV_{SAMMIE\ i}$: Field of vision estimated through SAMMIE CAD;

$FV_{EXP\ i}$: Field of vision measured experimentally;

n: Total number of measurements;

i: Each measurement.

3. Results

Ten utility ATV models were evaluated from six different manufacturers. Engine capacity ranged from 174 to 686 cc, with most vehicles in 400–600 cc (50 %). Moreover, 60 % of the ATVs evaluated included electric power steering (EPS), 4 wheel-drive (60 %), solid suspension (90 %), and manual transmission (50 %).

Findings from our first simulations showed that virtual obstacles placed at 0° did not influence the rider's field of vision, regardless of their distance from the ATV. For this reason, we removed those results from our further analysis. Furthermore, the results indicated that the use of a full-face helmet marginally affects the rider's field of vision, regardless of its use in conjunction with a sprayer tank or a windshield. For instance, we observed a maximum decrease of 0.03% in the rider's field of vision index when using a full-face helmet. Therefore, the hypothesis that a full-coverage helmet decreases riders' peripheral vision by approximately 3 % (Adhilakshmi et al., 2016) was not supported by our data. For this reason, these results were also removed from our analysis.

The percentage of ATVs (without a sprayer tank or a windshield) with visual limitation for youth is presented in Table 1. As an illustration, the percentage of ATVs with visual limitation for a simulated 8-year-old 5th percentile male is given in Fig. 6. Youth of both genders typically have visual limitations compared to their adult counterparts. Those limitations are more severe when considering obstacles at farther distances (≥1.5 m) or obstacles at 60°.

In general female youth had significantly fewer limitations than male youth. For example, 30% of the ATVs presented visual limitation for 16-year-old females. In contrast, that number was 43.3% for their male counterparts. Those differences are even more noticeable when considering the virtual obstacles individually. For instance, the percentage of ATVs with visual limitation for 16-year-old males and females when considering obstacles placed 1.5 m away from the vehicle at an angle of 60° were 73.3% and 23.3%, respectively: a substantial difference of 50%. Those differences are likely due to the different growth rates between males and females, where females usually reach their full anthropometric dimensions earlier than males (Chang et al., 2010).

Furthermore, the data clearly show a trend in youth's age. For instance, 63.3% of the ATVs presented visual limitations for males aged 8 years old. That number was consistently smaller for their older counterparts. The same tendency was observed for females. This trend is likely attributed to the differences in anthropometric dimensions of these youth. It was observed from the anthropometric database that the older the youth, the taller, regardless of their gender.

The percentage of ATVs (with a sprayer tank or a windshield) with visual limitations for youth are presented in Tables 2 and 3. Additionally, a comparison of the results for the various scenarios (ATVs with a sprayer tank or a windshield vs. ATVs without any equipment) is presented in Table 4.

The simulations involving a sprayer tank showed that riders are disproportionally affected by the addition of this equipment, thus confirming our hypothesis. While the percentage of ATVs with visual limitations increased for all youth, those limitations were more severe for youth younger than 13. For example, the percentage of ATVs with and without a sprayer tank that presented limitation for 12-year-old females was 83.3% and 50%, respectively. Moreover, the results indicated that, generally, the sprayer tank did not affect the rider's field of vision for obstacles located at 60° or 30°.

The simulations of the effects of a windshield on ATVs showed that, on average, youth have more visual limitations when a windshield is added. However, there were instances where the windshield actually improved the relative visibility. For example, the percentage of ATVs with visual limitations for 8-year-old female riders dropped from 63.3% for ATVs without a (frosted/dirty) windshield to 46.7% for ATVs with a windshield, a surprising difference of 16.6%. It is important to note that the determination of an ATV presenting visual limitations to youth is based on the comparison between their field of vision to that of adults. This difference of 16.6% indicates that, in some cases, the windshield has a similar effect on the field of vision of both adults and youth.

We emphasize that the addition of either a sprayer tank or a windshield inherently decreases the absolute field of vision of all riders. In fact, our results showed an average reduction in the rider's field of vision of 32.6% and 31.8% for ATVs installed with sprayer tanks and windshields, respectively (data not shown).

3.1. Validation

The outcomes of the validation tests are presented in Table 5. The results of the virtual simulations were very close to those of the field tests, with an RMSE of 0.99 squares, or 4.9%, indicating a high degree of accuracy. This suggests that the virtual simulations produced by SAMMIE CAD provide an accurate representation of the field of vision for both young ATV operators and adults, despite the difficulties of reproducing the exact same conditions in the field and the data representation error inherent in creating virtual ATVs. Overall, the validation process provides a confirmation of the conclusions drawn from the study and supports the use of SAMMIE CAD as a reliable tool for assessing field of vision in this context.

4. Discussion

Using a combination of actual field measurements and a novel digital simulation approach, the present study quantified the field of vision of simulated youth and adults (with or without a helmet) when riding

Table 1
Percentage of ATVs (no sprayer, no windshield) with visual limitations to youth (i.e., $E_r < 1.0$).

Gender	Age	Distance: 1.0 *m*			Distance: 1.5 *m*			Distance: 2.0 *m*			Total
		90	60	30	90	60	30	90	60	30	
Males	8	0.0	20.0	0.0	46.7	100.0	0.0	93.3	100.0	0.0	63.3
	9	0.0	16.7	0.0	43.3	100.0	0.0	93.3	100.0	0.0	56.7
	10	0.0	16.7	0.0	36.7	90.0	0.0	76.7	100.0	0.0	56.7
	11	0.0	10.0	0.0	40.0	83.3	0.0	76.7	100.0	0.0	53.3
	12	0.0	10.0	0.0	23.3	83.3	0.0	66.7	100.0	0.0	50.0
	13	0.0	10.0	3.3	23.3	80.0	0.0	60.0	96.7	0.0	56.7
	14	0.0	6.7	0.0	20.0	73.3	0.0	46.7	76.7	0.0	46.7
	15	0.0	6.7	3.3	13.3	53.3	0.0	30.0	66.7	0.0	36.7
	16	3.3	0.0	6.7	6.7	36.7	3.3	20.0	46.7	6.7	43.3
Mean	–	**0.4**	**10.7**	**1.5**	**28.1**	**77.8**	**0.4**	**62.6**	**87.4**	**0.7**	**51.5**
Females	8	3.3	30.0	0.0	46.7	86.7	0.0	100.0	100.0	0.0	63.3
	9	0.0	16.7	0.0	43.3	83.3	0.0	90.0	96.7	0.0	66.7
	10	0.0	20.0	0.0	43.3	83.3	0.0	83.3	96.7	0.0	60.0
	11	0.0	13.3	0.0	30.0	66.7	0.0	66.7	86.7	0.0	53.3
	12	3.3	10.0	0.0	30.0	50.0	0.0	46.7	76.7	0.0	50.0
	13	3.3	6.7	0.0	20.0	33.3	0.0	36.7	53.3	0.0	43.3
	14	10.0	6.7	0.0	16.7	23.3	10.0	16.7	43.3	0.0	40.0
	15	10.0	6.7	3.3	10.0	23.3	10.0	13.3	40.0	0.0	40.0
	16	6.7	3.3	3.3	10.0	16.7	13.3	6.7	30.0	0.0	30.0
Mean	–	**4.1**	**12.6**	**0.7**	**27.8**	**51.9**	**3.7**	**51.1**	**69.3**	**0.0**	**49.6**

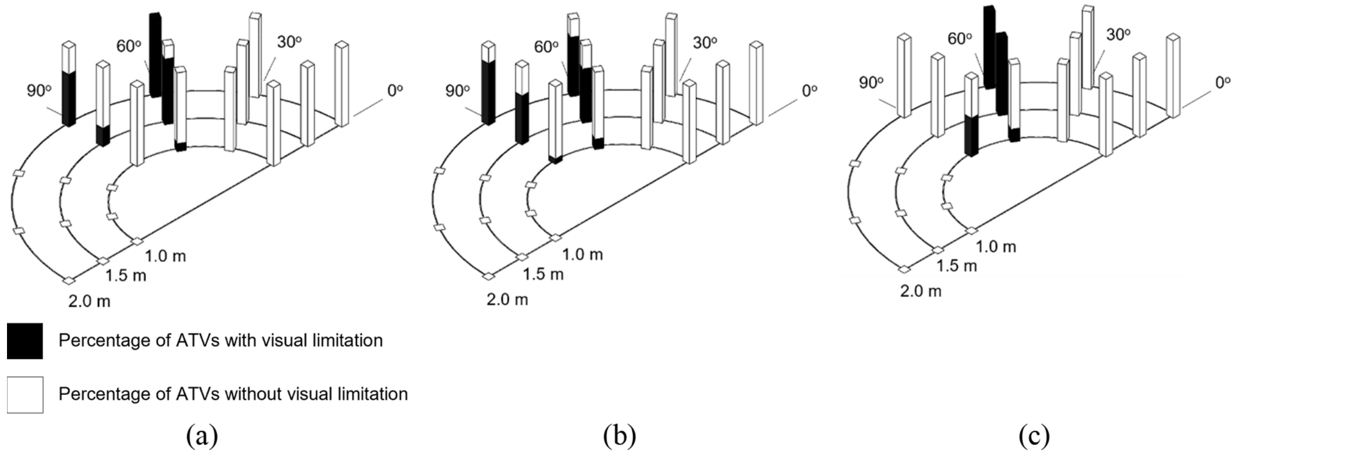

Fig. 6. Example of percentage of ATVs with visual limitation for a 8-year-old 5th percentile male. (a) ATV only, (b) ATV equipped with sprayer tank, (c) ATV equipped with windshield.

Table 2
Percentage of ATVs (with sprayer but no windshield) with visual limitations to youth (i.e., $E_r < 1.0$).

Gender	Age	Distance: 1.0 *m*			Distance: 1.5 *m*			Distance: 2.0 *m*			Total
		90	60	30	90	60	30	90	60	30	
Males	8	10.0	20.0	0.0	86.7	73.3	0.0	96.7	96.7	0.0	66.7
	9	10.0	16.7	0.0	83.3	73.3	0.0	96.7	86.7	0.0	66.7
	10	10.0	13.3	0.0	73.3	76.7	0.0	90.0	83.3	0.0	70.0
	11	10.0	20.0	0.0	73.3	76.7	0.0	90.0	73.3	0.0	63.3
	12	6.7	13.3	0.0	63.3	70.0	0.0	80.0	76.7	0.0	73.3
	13	0.0	10.0	0.0	56.7	63.3	0.0	80.0	80.0	0.0	63.3
	14	3.3	10.0	0.0	46.7	56.7	0.0	73.3	63.3	0.0	63.3
	15	3.3	3.3	0.0	43.3	46.7	0.0	60.0	40.0	0.0	56.7
	16	0.0	13.3	13.3	20.0	23.3	3.3	23.3	16.7	10.0	40.0
Mean	–	**5.9**	**13.3**	**1.5**	**60.7**	**62.2**	**0.4**	**76.7**	**68.5**	**1.1**	**62.6**
Females	8	20.0	13.3	0.0	86.7	86.7	0.0	100.0	100	0.0	83.3
	9	20.0	6.7	0.0	76.7	80.0	0.0	96.7	100	0.0	86.7
	10	20.0	6.7	0.0	80.0	76.7	0.0	96.7	100	0.0	86.7
	11	13.3	0.0	0.0	56.7	60.0	0.0	83.3	80.0	0.0	63.3
	12	13.3	0.0	0.0	43.3	50.0	0.0	76.7	63.3	0.0	66.7
	13	6.7	3.3	0.0	26.7	23.3	0.0	43.3	43.3	0.0	40.0
	14	3.3	0.0	0.0	16.7	13.3	10.0	33.3	26.7	0.0	36.7
	15	0.0	0.0	3.3	13.3	10.0	10.0	33.3	23.3	0.0	26.7
	16	0.0	0.0	3.3	6.7	3.3	13.3	20.0	10.0	3.3	20.0
Mean	–	**10.7**	**3.3**	**0.7**	**45.2**	**44.8**	**3.7**	**64.8**	**60.7**	**0.4**	**56.7**

Table 3
Percentage of ATVs (with windshield but no sprayer) with visual limitations to youths (i.e., $E_r < 1.0$).

Gender	Age	Distance: 1.0 *m*			Distance: 1.5 *m*			Distance: 2.0 *m*			Total
		90	60	30	90	60	30	90	60	30	
Males	8	10.0	66.7	0.0	0.0	100.0	0.0	0.0	100.0	0.0	70.0
	9	10.0	66.7	0.0	0.0	100.0	0.0	0.0	100.0	0.0	53.3
	10	10.0	33.3	0.0	0.0	100.0	0.0	0.0	100.0	0.0	70.0
	11	10.0	60.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	66.7
	12	10.0	30.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	86.7
	13	10.0	3.3	0.0	0.0	100.0	0.0	0.0	100.0	0.0	63.3
	14	6.7	0.0	0.0	0.0	100.0	0.0	0.0	96.7	0.0	43.3
	15	6.7	0.0	0.0	0.0	93.3	0.0	0.0	93.3	0.0	86.7
	16	6.7	0.0	0.0	0.0	93.3	0.0	0.0	86.7	0.0	40.0
Mean	–	**8.9**	**28.9**	**0.0**	**0.0**	**98.5**	**0.0**	**0.0**	**97.4**	**0.0**	**64.4**
Females	8	33.3	30.0	0.0	0.0	60.0	0.0	0.0	66.7	0.0	46.7
	9	46.7	40.0	0.0	0.0	90.0	0.0	0.0	100.0	0.0	63.3
	10	33.3	33.3	0.0	0.0	93.3	0.0	0.0	100.0	0.0	66.7
	11	33.3	23.3	0.0	0.0	86.7	0.0	0.0	100.0	0.0	53.3
	12	23.3	20.0	0.0	0.0	66.7	0.0	0.0	93.3	0.0	43.3
	13	13.3	10.0	0.0	0.0	53.3	0.0	0.0	80.0	0.0	56.7
	14	10.0	0.0	0.0	0.0	36.7	0.0	0.0	63.3	0.0	40.0
	15	16.7	0.0	0.0	0.0	33.3	10.0	0.0	60.0	0.0	53.3
	16	13.3	0.0	3.3	0.0	20.0	10.0	0.0	50.0	0.0	43.3
Mean	–	**24.8**	**17.4**	**0.4**	**0.0**	**60.0**	**2.2**	**0.0**	**79.3**	**0.0**	**51.9**

Table 4
Differences in the mean percentage of ATVs with visual limitations to youth based on the type of equipment attached to it.

Equipment	Gender	Distance: 1.0 *m*			Distance: 1.5 *m*			Distance: 2.0 *m*			Total
		90	60	30	90	60	30	90	60	30	
Sprayer	Males	−5.6	−2.6	0.0	−32.6	15.6	0.0	−14.1	18.9	−0.4	−11.1
	Females	−6.7	9.3	0.0	−17.4	7.0	0.0	−13.7	8.5	−0.4	−7.0
Windshield	Males	−8.5	−18.1	1.5	28.1	−20.7	0.4	62.6	−10.0	0.7	−13.0
	Females	−20.7	−4.8	0.4	27.8	−8.1	1.5	51.1	−10.0	0.0	−2.2

Table 5
Number of visible squares for each subject during the validation tests.

Simulation type	Subject	Windshield	Distance = 1.0 *m*			Distance = 1.5 *m*			Distance = 2.0 *m*		
			90°	60°	30°	90°	60°	30°	90°	60°	30°
Field tests	1	No	12	12	14	12	12	20	15	15	20
		Yes	4	8	14	4	10	20	5	12	20
	2	No	12	12	14	12	12	18	15	15	20
		Yes	4	8	14	4	9	18	4	12	20
SAMMIE CAD	1	No	9	9	12	11	12	18	13	15	20
		Yes	3	8	14	2	9	18	2	12	20
	2	No	9	9	12	11	12	18	13	15	20
		Yes	3	8	14	2	9	18	2	12	20

various ATV models with or without a sprayer tank or a (frosted/dirty) protective windshield. The major finding was that, compared to an adult operator, youth, especially those younger than 12 years old, have compromised field of vision. This finding infers that youth operators will likely not see an obstacle or a bystander that is in the surrounding of the ATV. As such, youth become more likely to hit obstacles, which is one of the most common causes of ATV crashes (Balthrop et al., 2007; Concannon et al., 2012; Helmkamp et al., 2011; Jennissen et al., 2018; Lower & Herde, 2012). The higher possibility of youth operators to hit stationary obstacles offers one potential explanation to youth's disproportionately large mortality rate relative to adults in ATV crashes (Altizer, 2008; Bernard et al., 2010; Su et al., 2006).

4.1. Farming equipment

Windshields have been arguably pointed out as detrimental to youth safety. However, it is important to emphasize that the arguments presented in this study were formulated based on a windshield without proper maintenance (e.g., completely dirty or frosted). The authors have no objection whatsoever to the use of windshields provided they are properly maintained and free of visual impediments. Therefore, the interpretation and generalization of the present results should be carried out carefully. Conversely, the results showed that sprayer tanks mounted in the front rack of the ATV inherently reduce the rider's field of vision. Whenever possible, we recommend that sprayer tanks be mounted in the rear rack of the ATV or placed in a wagon/trailer towed by the ATV.

4.2. Recommended changes in guidelines and policies for youth operating ATVs

The establishment of minimum age for ATV operation is a major focus for researchers and regulatory agencies concerned with rural children's safety and health. The American Academy of Pediatrics (AAP) recommends that children younger than 16 years old should not ride ATVs (American Academy of Pediatrics, 2018). However, the present findings showed that some children younger than 16 years old, especially females, have small visual limitations compared to their adult counterpart. Alternatively, the U.S. Consumer Product Safety Commission (CPSC) recommends that youth-ATV fit should be based on ATV's engine size, while the American National Standard Institute (ANSI/SVIA) suggests ATV maximum speed (the maximum speed the ATV could potentially achieve - a static specification provided by the manufacturer) as a fit criterion (ANSI/SVIA, 2017; CPSC, 2006). Nevertheless, the average total FVI is not correlated to ATV engine size ($r = -0.06$, p-value = 0.85) nor vehicle's maximum speed ($r = -0.15$, p-value = 0.66). The present findings, along with the results of two recent studies regarding the forces required for effective ATV operation (De Moura Araujo et al., 2022b) and the ability of youth to physically reach all ATV controls (De Moura Araujo et al., 2022a) provide quantitative and systematic evidence to modify/update current ATV safety guidelines. Furthermore, youth occupational health professionals could use the present findings to reduce the number of ATV-related incidents in agricultural and other settings.

4.3. Study limitations

Several limitations warrant attention when interpreting the results of the present study. First, the virtual human mockups were generated based on an anthropometry study completed in 1977 (Snyder et al., 1977). This 46-year gap requires caution in the interpretation and generalization of the current findings since it is reasonable to assume potential discrepancies between children in 1977 and their counterparts of 2023.

Second, the sampling of ATV models was not random and is subject to sampling error, although the approach was systematic and logical. Thus, even though the approach targeted the most commonly used ATVs by farmworkers in the United States, the sample may not necessarily represent all ATVs operated specifically by youth.

Third, safe and effective riding of utility ATVs involves consideration of several other issues besides the ability of youth to perceive obstacles around the ATV, such as the ability to reach and activate operational controls (Bernard et al., 2010; De Moura Araujo et al., 2022a; De Moura Araujo et al., 2022b) and take calculated decisions to avoid hazards (Jennissen et al., 2017; Khorsandi Kouhanestani et al., 2022). Furthermore, ATVs are rider-active vehicles, which means that riders must be able to shift their body weight to safely perform maneuvers such as turning, negotiating hills, and crossing obstacles (Jennissen et al., 2014; National 4-H Council, 2005). These circumstances warrant further investigation.

Fourth, the 3-D representation of the ATV models evaluated in this study is simple and does not include several features, such as the fuel tank, rear-basket, among others. However, all the key components that are necessary for basic ATV operation were included. In addition, the virtual simulations were validated with experimental tests.

Fifth, all human mockups were placed at the ATVs' seat reference point (SRP). This scenario may not provide the most accurate depiction of ATV riding for many riders since many do not sit at the SRP (Jennissen et al., 2014). For instance, small children tend to sit a bit forward of the SRP to allow control reaching, while taller adults tend to sit behind the SRP for the same reason. However, the SRP is a standardized expected seat position, which allowed for a consistent evaluation approach among the various conditions. The effect of sitting adaption in the field of vision requires further assessment.

Finally, the simulations were performed with static human mockups, that is, we did not evaluate any trunk or hip movement. In real riding situations, riders may shift their hips forward and/or bend their trunks to reach a control or perform active riding, affecting riders' field of vision. However, these effects were not evaluated due to feasibility issues.

5. Summary

The present study evaluated limitations in the field of vision of simulated youth operators when riding commonly used utility ATVs under diverse riding scenarios. The main findings were that: (1) youth younger than 16 years old typically have restricted field of vision compared to adults; (2) sprayer tanks and (poorly maintained) windshields reduce the rider's field of vision, on average, by more than 30%; and (3) only engine size, vehicle maximum speed, and rider's age are poor indicators of youth-ATV fit. The present findings, along with the results of recent studies regarding the forces required for effective ATV operation and the physical ability of youth to reach ATV controls (De Moura Araujo et al., 2022a; De Moura Araujo et al., 2022b), raise serious questions about the ability of children to safely operate utility ATVs in common use on U.S. farms and about the validity of current youth-ATV fit guidelines.

6. Practical applications

The present study provides quantitative and systematic data comparing the visual acuity of youth and adults in the context of ATV operation in an occupational setting. These data support manufacturers in considering design changes or manufacturing new machines and provides critical evidence contributing to the scientific basis for modifying regulatory/advisory guidelines for youth operating utility ATVs.

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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