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Physical and cognitive capabilities of children during operation and evacuation of a school bus emergency roof hatch

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ABSTRACT

While many school bus routes exclusively transport kindergarten, first, and second grade (K-2) children, school bus emergency exits are designed based on the physical capabilities of an average adult male. This makes the usability of emergency exits less than optimal for K-2 children. The objective of this study was to determine if children in (K-2) are capable of opening and evacuating from a school bus roof hatch in an emergency rollover scenario. Maximum push force exertions of 91 K-2 students were measured during operation of a typical school bus emergency roof hatch (designed to meet Federal Motor Vehicle Safety Standard [FMVSS] No. 217 specifications). Ability to read and comprehend emergency-related words and roof hatch operating instructions was also evaluated for 58 students. Forty-two percent (42%) of kindergarten students were unable to exert the maximum permissible design force (89 N) necessary to operate the roof hatch. Only 20% of the participants in kindergarten were able to open the roof hatch. In a controlled environment, the majority of students (96%) were willing and able to self-extricate through the opening. However, only 33% of students had the cognitive skills necessary to understand how to open the roof hatch. Eighty-nine percent (89%) of participants who completed both the physical and cognitive aspects of the study were unable to successfully operate the school bus roof hatch.

1. Introduction

School buses in the United States transport approximately 26 million children daily. Despite being the safest mode of student transportation, approximately 26,000 school bus accidents occur every year (NASDPTS, 2000; McCray and Brewer, 2005). While emergency evacuation training is performed twice per year in many school districts across the country (no federal standard exists and state regulations vary), the training is typically focused on evacuating through the front and rear emergency doors of school buses when the school bus is in a standard orientation. School bus rollover accidents are often viewed as the most complex and dangerous type of accidents since occupants are unfamiliar with the rolled-over bus orientation. Roof hatches are one of the primary means of egress for rollover bus accidents (Matolcsy, 2010) with strength and stature being factors affecting both usability and egress rates (Pollard and Markos, 2009). Testing the ability of younger school bus riders to self-extricate through a roof hatch is critical for assessing the effectiveness of the current emergency evacuation system, particularly because training is not typically provided during school bus emergency evacuation training (emergency roof hatch evacuation training is rarely performed to prevent students from operating the device during normal transport). For children to operate the roof hatch, they also must be able to read and understand the instructions written on the hatch.

1.1. Roof hatch standards

Federal Motor Vehicle Safety Standard (FMVSS) No. 217 specifies that the maximum permissible force allowed to operate the release mechanism of a school bus roof hatch is 89 N or less. These force requirements were developed considering the physical capabilities (including stature) of an average adult male (Pollard and Markos, 2009). The primary occupants of most school buses are young children that do not have the physical capabilities and stature characteristics to meet

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these requirements. In many instances, the bus driver is the only adult on the school bus. Should the driver be incapacitated due to illness, injury, or any other reason, it may be solely up to the children to evacuate the bus until further adult assistance arrives. The difficulty in evacuating passengers from bus accidents influences post-crash injury outcomes (Peden et al., 2004). Therefore, it is important to determine if children in kindergarten through second grade (K-2) have the physical and cognitive capabilities to operate and evacuate through the roof hatch of a rolled-over school bus without adult intervention.

1.2. Strength capabilities of children

A Consumer and Competition Policy Directorate of the Department of Trade and Industry study measured the strength of children and adults to provide reference data for use in the design of safer products (Department of Trade and Industry, 2002). Maximum push exertions using two or more fingers of the participant's dominant hand on a (50 mm × 50 mm) plastic cube ranged from 7 N to 35 N for 2–5 year old males ($\bar{x}$ = 27 N, SD = 13), and 36 N to 125 N for 6–10 year old males ($\bar{x}$ = 66 N, SD = 24). Similarly, Peebles and Norris (2003) found that index finger push force on a 20 mm circular diameter force plate ranged from 16 N to 35 N for 2–5 year old males ($\bar{x}$ = 20 N, SD = 5) and 31 N to 62 N for 6–10 year old males ($\bar{x}$ = 52 N, SD = 13).

Based on these two studies, the average push force for young children was lower than the 89 N maximum established in FMVSS No. 217 for roof hatch operation (NHTSA, 2011). Furthermore, the push forces measured in these studies are likely to be higher than that which can be exerted on a roof hatch knob since there is less surface area on which to exert the force (16.3 cm^2 for the roof hatch vs. 25.8 cm^2 for the plastic cube). Additionally, the location of the force plate in the studies was at the participants' elbow height affording a relatively favorable posture and the potential to use body weight. The relative location of the roof hatch knob for children is much higher (above elbow height) than for adults. An average kindergarten age child would have to reach over their shoulder to push the roof hatch knob, whereas the average adult could use their body weight while pushing on the knob (see Fig. 1).

1.3. Cognitive abilities of children

During the early elementary years, children go through substantial cognitive development including increasing the number of items held in their mind after a delay [Gathercole, 1998], updating working memory with new information (Hongwanishkul et al., 2005), and both verbal and nonverbal tasks (Alloway et al., 2004). Reading ability, specifically, goes through rapid development during the elementary years. Children at this stage largely rely on memory of words and are still learning to decode (Ehri, 2008). At this stage, word identification accounts for over half of the variance in reading comprehension. To understand the written instructions on the roof hatch, students must be able to identify or decode each of the words on the hatch. Assuming the children can read the instructions, the next step is for them to be able to understand and follow the instructions. This requires children to “hold” the instructions in their mind as they are acting them out. Currently, there is no research on the abilities of children to read emergency-related words or to understand emergency instructions.

1.4. Study aims

The overarching goal of this study was to determine if children in kindergarten, first, and second grade are capable of opening and evacuating from a school bus roof hatch in an emergency rollover scenario. To address this goal, we established two primary aims. The first was to characterize the strength capabilities of children to determine whether they have the ability to operate and exit through the emergency escape roof hatch on a school bus. Specifically, we aimed to determine:

1a. The maximum push force and torque that can be exerted on a roof hatch knob by children in K-2.
1b. Whether K-2 students are able to disengage the release mechanism and open a school bus emergency escape roof hatch.
1c. Whether K-2 students have the physical capabilities to self-extricate through a roof hatch of a school bus in a rolled-over orientation.

The second aim of the study was to investigate if children can read, define, and act out the instructions written on the roof hatch by determining:

2a. If there are grade-related differences in the ability to read emergency-related words and if this differs from non-emergency related sight words.
2b. If there are grade-related differences in the ability to define emergency-related words and if this differs from non-emergency related sight words.
2c. If children can read the roof hatch instructions and follow the

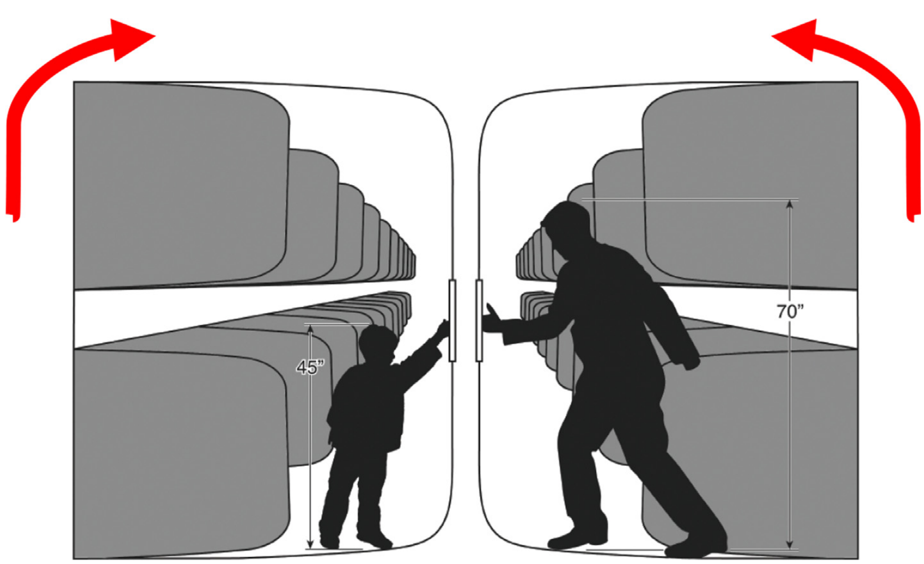

Fig. 1. Scaled illustration of rolled-over school bus.

Table 1
Study participants.

	Both studies	Physical only	Cognitive only	Total
Kindergarten	18 (10 male)	12 (8 male)	–	30 (18 male)
1st Grade	20 (9 male)	14 (10 male)	5 (4 male)	39 (23 male)
2nd Grade	14 (7 male)	13 (7 male)	1 (0 male)	28 (14 male)

Table 2
Participants demographic and anthropometric data.

Kindergarten (n = 30)	Mean	SD	Minimum	Maximum
Age (years)	5.8	0.4	5.3	6.8
Weight (kg)	22.0	5.5	14.5	42.0
Height (cm)	114.8	5.6	105.4	126.3
Hand width (cm)	6.1	0.6	4.9	8.3
Hand length (cm)	12.0	0.9	9.6	14.0
1st Grade (n = 34)	Mean	SD	Minimum	Maximum
Age (years)	6.9	0.4	6.3	8.0
Weight (kg)	25.5	6.6	17.7	54
Height (cm)	121.9	6.3	114.1	137.8
Hand width (cm)	6.2	0.4	5.5	7.3
Hand length (cm)	13.1	0.8	11.2	14.7
2nd Grade (n = 27)	Mean	SD	Minimum	Maximum
Age (years)	8.4	0.6	7.8	9.8
Weight (kg)	32.6	11.9	17.5	67.6
Height (cm)	130.4	8.3	111.4	149.2
Hand width (cm)	6.7	0.6	5.4	8.2
Hand length (cm)	14.2	0.9	11.7	15.8

instructions.

2. Method

2.1. Participants

A total of 97 kindergarten, first grade, and second grade students were recruited from grade specific physical education classes at Jim Pearson Elementary School in Alexander City, AL (Table 1). Because of time restrictions and other logistical issues (e.g., student absence, etc.), some students (N = 91) participated in only the physical portion of the study (Table 2). Fifty-two students participated in both the physical capabilities and cognitive portions of the study that were completed on separate days. This research complied with the American Psychological Association Code of Ethics and was approved by the Institutional Review Board at Auburn University. Approved letters of consent were distributed by the school to parents and guardians prior to the study. Parental consent and child assent were required to participate in the study.

2.2. Materials & procedure

2.2.1. Equipment

A section of a 2013 Blue Bird Vision school bus was used to construct the roof hatch test apparatus shown in Fig. 2. Though roof hatches have different features and designs, most use similar operating mechanisms and have similar sized openings (22 in. × 22 in.). The roof hatch used in this study is representative of those typically employed on a majority of school buses. To release the roof hatch, a passenger must (i) turn the red knob from "latched" to the "to exit" position, and (ii) push "sharply upward" on the red knob to open it [Blue Bird Bus Corporation, 2008]. The roof hatch used in this study was a Transpec™ 1970 Series Standard Safety Vent (Fig. 3).

2.2.2. Physical abilities procedure

Participants rotated between three data collection stations. Demographic data (height, weight, hand measurements, gender, grade level, and age) were recorded at the first station. At the second station, each participant's ability to open and self-extricate through the roof hatch was evaluated. Participants were asked to stand in front of the roof hatch apparatus (Fig. 2) and were shown how to unlatch the roof hatch by a researcher. The time from touching the roof hatch knob until the roof hatch was disengaged was recorded. If the participant was unable to operate the roof hatch release mechanism within 30 s, the roof hatch was opened for them. The participant was then asked to self-extricate through the opening. Time to evacuate through the roof hatch was recorded from the time they touched the roof hatch opening until their entire body was through the roof hatch opening. It is important to note that performance of subjects during the evacuation was conducted under favorable conditions. Participants were not subject to disorientation, the presence of debris, or injuries resulting from a rollover accident. If the participants did not want to evacuate, they were asked a second time. If they declined, the experiment was stopped. Research assistants monitored the evacuation process and provided assistance as required.

Force and torque measurements were recorded at the third station. Force and torque stands equipped with a push-pull dynamometer and a torque transducer were built to replicate the location of the roof hatch knob in a rolled-over school bus as shown in Fig. 4. Participants were asked to perform three maximal push force and torque exertions on the roof hatch knob. A 30 s rest interval was provided between trials.

2.2.3. Cognitive abilities procedure

Participants were tested in a classroom individually. First, participants took a word and phrase reading assessment. In this assessment, words were presented on a computer screen and participants were instructed to read the word out loud. If they were unable to do so, the researcher read the word out loud. Participants were then instructed to define the word. Once all of the words were completed, participants completed the phrase reading and acting out assessment. Participants were instructed to read a phrase out loud and act out the phrase. If participants were unable to read the phrase, the researcher read the phrase and instructed the participants to act it out. Finally, a standardized intelligence test, The Kaufman Brief Intelligence Test, 2nd Ed. (KBIT-2; Kaufman & Kaufman, 2004) was administered. The total administration time was approximately 30 min per participant.

For the word-reading portion of the experiment, participants were required to read, out loud, individual words that were presented on a computer screen. A total of 28 words were used in the study, including four control words each from the Kindergarten, Grade 1, and Grade 2 Dolch sight word lists (*Kindergarten: eat, soon, good, and went; Grade 1: give, ask, old, and walk; and Grade 2: sing, green, wish, and cold*). Fifteen emergency-related words were also tested. These words were taken from the instructions on various roof hatches (*open, handle, exit, push, locked, lever, latched, turn, door, pull, lift, knob, unlock, evacuate, and emergency*). A final word, *ventilation*, was also tested because it appears on many roof hatches. Two counterbalanced conditions were used, each with half of the control words (two words each from each grade level), and seven randomly selected emergency related words. However, all participants read the words *emergency* and *ventilation*. In total, each participant read and defined 15 words. The counterbalanced conditions were used to decrease the number of words that each child had to read to ensure that the experiment could be completed in the allotted time. The conditions also allowed investigation of potential differences in performance of specific words.

The next part of the experiment required participants to read two phrases out loud and act out the phrases. The first phrase was a practice phrase, "*Put your hand on your head and stand on one foot*". The second phrase was taken directly from the roof hatch that was tested, "*TURN THEN PUSH KNOB TO OPEN*".

Fig. 2. Roof hatch evacuation test apparatus.

Fig. 3. Transpec™ 1970 series standard safety vent roof hatch.

Fig. 4. Torque and push force measurement stands.

Finally, the KBIT was administered to each of the participants to obtain a baseline measure of cognitive ability, ensuring that participants were within the normal range. This was critical to interpret if the emergency related words and instructions were more difficult than typical children in grades K-2 are capable of processing. This test includes a verbal subtest that involves identifying pictures of words, and a non-verbal test that involves identifying pictures and patterns that completed a set. The normed average is 100 with a standard deviation of 15.

2.3. Data analysis

For the physical abilities experiment, the independent variables were: grade level (kindergarten, first grade, second grade), height, weight, gender, hand length, and hand width. Dependent variables included: push force exerted on the roof hatch knob, ability to unlatch the roof hatch (dichotomous), and the ability to self-extricate through the emergency roof hatch (dichotomous). Best subsets regression was used to develop a model with the best predictor variables that affected push force. The effects of the independent variables on opening the roof hatch and self-extricating through the roof hatch were analyzed using stepwise logistic regression to determine the best fitting model and minimize multicollinearity of the independent variables.

For the cognitive abilities experiment, the independent variable was grade level (kindergarten, first grade, second grade). Dependent variables included word reading accuracy (for sight words and emergency-related words), definition accuracy (for sight words and emergency-related words), accuracy in reading the roof hatch instructions, and accuracy in acting out the instructions with the help of the researcher. A series of one-way ANOVAs were conducted on each of these dependent variables using grade as the independent variable ($\alpha = 0.05$).

3. Results

3.1. Force exertions and roof hatch operation

Descriptive statistics of torque and push force measurements, time to unlatch the roof hatch, and self-extrication time are provided in Table 3. While only 20% (6/30) of the kindergarten participants were able to open the roof hatch, 87% (26/30) were willing and able to self-extricate. For first grade, 71% (24/34) were able to open the roof hatch, and 91% (31/34) were able and willing to self-extricate. 89% (24/27) of the second grade participants were able to open the roof hatch, and 96% (26/27) were willing and able to self-extricate. Two data points were excluded from the analyses of the data. One of the participants in the first grade chose not to participate in the study after anthropometric data were collected. Push force data for one of the second grade participants was excluded due to an inaccurate reading from the push-pull dynamometer.

Flow rate is a common measure of emergency exit effectiveness during an evacuation. Exits with a high flow rate indicate that more people can move through it during an evacuation. The mean flow rate (children/minute) for the roof hatch was calculated by dividing 60 s by the roof hatch evacuation time for each individual at each grade level

Table 3
Descriptive statistics of physical abilities study.

Kindergarten (N = 30)	Mean	SD	Minimum	Maximum
Trial 1 – Torque (Nm)	1.78	0.49	0.90	2.59
Trial 2 – Torque (Nm)	1.71	0.47	0.83	2.52
Trial 3 – Torque (Nm)	1.56	0.52	0.77	2.60
Maximum Torque Trial (Nm)	1.86	0.49	0.94	2.60
Trial 1 – Push Force (N)	67.3	24.5	24	118
Trial 2 – Push Force (N)	70.1	25.8	20	142
Trial 3 – Push Force (N)	71.5	24.1	28	132
Maximum Push Force Trial (N)	79.1	26.3	32	142
Time from touching roof hatch to hatch unlatched (seconds)	9.1	4.8	3.7	17.9
Time from hatch unlatched to entire body on other side of hatch (seconds)	6.9	3.6	2.5	15.9
1st Grade (N = 34)	**Mean**	**SD**	**Minimum**	**Maximum**
Trial 1 – Torque (Nm)	2.09	0.62	0.94	4.11
Trial 2 – Torque (Nm)	2.02	0.62	1.00	3.32
Trial 3 – Torque (Nm)	2.06	0.68	1.03	3.61
Maximum Torque Trial (Nm)	2.43	0.60	1.22	4.11
Trial 1 – Push Force (N)	91.8	25.5	24	148
Trial 2 – Push Force (N)	91.3	26.6	20	148
Trial 3 – Push Force (N)	96.0	27.4	30	168
Maximum Push Force Trial (N)	101.3	26.6	30	168
Time from touching roof hatch to hatch unlatched (seconds)	7.2	3.4	2.2	14.9
Time from hatch unlatched to entire body on other side of hatch (seconds)	5.2	2.9	1.1	17.9
2nd Grade (N = 27)	**Mean**	**SD**	**Minimum**	**Maximum**
Trial 1 – Torque (Nm)	2.67	0.89	0.93	4.75
Trial 2 – Torque (Nm)	2.46	0.85	0.88	4.67
Trial 3 – Torque (Nm)	2.43	0.79	0.81	4.14
Maximum Torque Trial (Nm)	2.91	0.95	0.93	4.75
Trial 1 – Push Force (N)	114.4	29.7	64	206
Trial 2 – Push Force (N)	116.2	30.6	66	191
Trial 3 – Push Force (N)	118.9	39.7	60	240
Maximum Push Force Trial (N)	125.2	37.2	66	240
Time from touching roof hatch to hatch unlatched (seconds)	5.2	2.9	1.4	12.2
Time from hatch unlatched to entire body on other side of hatch (seconds)	5.7	5.1	2.3	28.8

Table 4
Roof hatch flow rate (Children per Minute).

Grade	Flow rate (PPM)	SD	Minimum	Maximum
Kindergarten	11	6	4	24
First Grade	15	10	3	57
Second Grade	14	6	2	26

(Table 4).

The percentage of children not capable of exerting the maximum permissible force requirements are summarized in Table 5. Gender was determined not to be a statistically significant factor for maximum push force ($F_{1, 85} = 0.06$, $p > 0.05$). However, grade level was a statistically significant factor ($F_{2, 85} = 16.28$, $p < 0.001$).

The results of the most parsimonious best subset regression model are shown in Table 6. Weight and hand length had a statistically significant effect on maximum push force ($p < 0.05$), and the adjusted R^2 of the model was 58.61%. As illustrated in Table 7, the independent variables that best fit the logistic regression model for opening the roof hatch were height and grade level. Height had a statistically significant effect on the ability to open the roof hatch ($p < 0.001$), whereas grade level was marginally significant ($p = 0.055$). A similar logistic regression was performed on the self-extrication data, but no independent variables were determined to be statistically significant.

Table 5
Percentage of children not capable of exerting ≥89 N by grade.

Grade	Percentage
Kindergarten	18/30 = 60%
1st grade	14/33 = 42%
2nd grade	4/26 = 15%

Table 6
Maximum push force regression.

Source	DF	Adj SS	Adj MS	F	p
Regression	6	62,601	10433.5	19.35	< 0.001
Weight	1	9678	9678.4	17.95	< 0.001
Hand Width	1	1254	1254.2	2.33	0.13
Hand Length	1	2203	2203.2	4.09	0.05
Grade	2	813	406.3	0.75	0.47
Gender	1	917	916.7	1.7	0.20
Error	82	44,204	539.1		
Total	88	106,805			

Table 7
Opening roof hatch stepwise logistic regression.

Source	DF	Adj SS	Adj Mean	Chi-Square	p
Regression	3	47.14	15.71	47.14	< 0.001
Height	1	14.24	14.24	14.24	< 0.001
Grade	2	5.78	2.89	5.78	0.06
Error	87	75.82	0.87		
Total	90	122.96			

3.2. Cognitive abilities

3.2.1. KBIT scores

An ANOVA on the verbal and nonverbal subsections of the KBIT was conducted with grade included as the independent variable. There was not a significant difference in performance on the verbal subsection of the KBIT based on grade ($F_{1, 56} = 1.79$, $p = .18$), nor was there a difference in performance on the nonverbal section based on grade ($F_{1, 56} = .41$, $p = .66$). Descriptive statistics for each subtest and the total score are provided in Table 8. T-tests comparing mean performance on each subtest against the normalized average (1 0 0) revealed that performance was significantly lower than expected for both the verbal test ($t_{56} = -4.55$, $p < .001$), and the non-verbal test, ($t_{56} = -2.50$, $p = .02$). Upon examination of the data, there were 9 scores that were lower than 2 standard deviations below the mean for the verbal score and 1 score that fell below 1 standard deviation for the nonverbal scores. All subsequent analyses were conducted twice, one analysis included these data points and one analysis excluded these data points. The overall pattern of performance did not differ when these data were removed, so all reported analyses included all of the data points.

Table 8
Descriptive statistics for the KBIT, emergency word reading and emergency word definitions.

	KBIT verbal mean (SD)	KBIT nonverbal mean (SD)	KBIT total mean (SD)	Emergency words (Reading)	Emergency words (Definitions)
Kindergarten	94.06 (16.56)	94.94 (11.52)	94.12 (12.81)	.13 (.24)	.60 (.20)
1st grade	91.24 (16.87)	94.16 (12.43)	91.60 (13.63)	.30 (.32)	.66 (.20)
2nd grade	83.53 (14.81)	98.20 (18.09)	89.60 (16.00)	.70 (.29)	.71 (.18)

Table 9
Word reading and definition accuracy for emergency-related words.

	Reading accuracy Mean (SD)	Definition accuracy Mean (SD)
Push	.54 (.51)	.92 (.27)
Open	.42 (.50)	.96 (.20)
Lever	.42 (.50)	.11 (.33)
Door	.42 (.50)	.93 (.25)
Pull	.42 (.50)	.72 (.46)
Lift	.35 (.49)	.53 (.51)
Unlock	.35 (.49)	.81 (.40)
Exit	.35 (.49)	.58 (.50)
Locked	.35 (.49)	.92 (.27)
Latched	.35 (.49)	.19 (.40)
Handle	.31 (.47)	.69 (.47)
Turn	.26 (.44)	.72 (.46)
Emergency	.23 (.42)	.84 (.37)
Ventilation	.11 (.32)	.00 (.00)
Evacuate	.19 (.40)	.22 (.42)

3.2.2. Word reading

The first aim of the cognitive assessment was to determine if there are grade related differences in the ability to read emergency-related words. A one-way ANOVA showed large grade-related differences ($F_{2, 57} = 16.12$, $p < .001$), with second grade students substantially outperforming both the first grade students and the kindergarten students (Table 9). This difference was also observed for sight words from the kindergarten, first grade, and second grade reading lists ($F_{2, 55} = = 26.99$, $p < .001$). In summary, children in the different grades had substantially different abilities related to reading individual words. Word reading accuracy was also analyzed for each emergency related word. There were large differences in accuracy, with *evacuate* having the lowest accuracy, $M = .06$, $SD = .25$, and *push* having the highest level of accuracy, $M = .54$, $SD = .51$ (Table 10).

3.2.3. Definitions

The second aim of the cognitive assessment was to determine if there are grade-related differences in the ability to define words. A one-way ANOVA showed that there was not an effect of grade on the ability to define emergency-related words, ($F_{2, 57} = 1.19$, $p = .31$; Table 8). Mean definition accuracy ranged from, $M = .60$, $SD = .20$, for the kindergarten participants to, $M = .71$, $SD = .18$, for the second grade participants (Table 9). Definition accuracy for the sight words did not differ by grade ($F_{2, 55} = 1.89$, $p = .16$). Therefore, although there appear to be grade-related changes in word reading, there are not substantial changes in the ability to define the words presented in this study.

3.2.4. Reading and understanding phrases

Large grade-related differences in the ability to read the phrases evaluated in this study were observed, ($F_{2, 57} = 8.79$, $p < .001$; Table 10). No grade related differences were observed in the ability to act out the phrase, ($F_{2, 56} = .12$, $p = 0.88$). Statistically significant differences between grades were observed for the ability to read the phrase, understand it, and act it out without the help of the researcher ($F_{2, 57} = 4.25$, $p = 0.02$). Although the second grade participants were significantly better at this task than the kindergarten participants, only 33% of the second grade participants could read, understand, and act out the roof hatch instructions.

Table 10
Phrase reading and acting out instructions accuracy.

	Reading accuracy	Act out phrase (Total)	Act out phrase (Read on own)
Kindergarten	.11 (.32)	.72 (.46)	.00 (.00)
1st grade	.32 (.48)	.75 (.44)	.12 (.33)
2nd grade	.73 (.46)	.80 (.41)	.33 (.49)

4. Discussion

The overall goal of this study was to determine if children in kindergarten, first, and second grade are capable of opening and evacuating from a school bus roof hatch in an emergency rollover scenario. The capability of opening a roof hatch depends both on the child's ability to understand the written instructions and to physically open the hatch. Few children were able to read and understand the roof hatch instructions well enough that they could act out the instructions on their own. *When paired with the physical data, only 11% (6/52) of participants who completed both portions of the study were able to understand the instructions, act them out, and exert the force necessary (as defined by standard FMVSS No. 217) to open the emergency escape roof hatch.*

While most of the first and second grade students were capable of exerting enough push force to open the roof hatch, the maximum push force data collected in this study suggested that push force exerted by kindergarten students is less than the maximum permissible force specified by standard FMVSS No. 217. Weight had a significant effect on the amount of push force the children exerted, while strength differences between males and females were not substantially different in this age range. Hand length appears to be predictive of greater hand strength, which would allow for greater force exertions. It is important to note that the children were in an ideal environment when performing the push force exertion. Factors such as injuries and obstructions inside and outside the school bus may hinder their ability to open the roof hatch in an actual emergency.

All participants were able to exert enough torque on the roof hatch knob to rotate it to the "to exit" position. Participants unable to open the roof hatch were unable to exert enough push force to disengage the locking mechanism. The main reasons participants were unable to self-extricate through the roof hatch opening were apparent insufficient upper body strength and/or low friction between the smooth ceiling surface surrounding the roof hatch and their feet. While many school districts have mixed grade routes where the older students can open the roof hatch in the event of a rollover accident, most districts use school buses to transport only kindergarten-aged students for special events such as field trips.

Though some students were able to open the roof hatch and self-extricate, it is important to consider the flow rate through the roof hatch to evaluate its performance in an emergency egress scenario. The extrapolated flow rates of children through the emergency roof hatch is comparable to the 12 people per minute flow rate measured by the Volpe Center from a motorcoach roof hatch (Pollard and Markos, 2009). The Volpe Center measured the flow rate of a motorcoach roof hatch exit by conducting egress trials on a rolled-over motorcoach and using employees with sufficient knowledge on operating roof hatches (Pollard and Markos, 2009). Similarly, the Volpe Center measured the mean time required to open a motorcoach roof hatch to be six seconds, and as illustrated in Table 3 the mean opening time ranged between 5.22 s and 9.1 s for K-2 participants. However, it is important to note that participants were given verbal instructions on how to open the roof hatch and they had no prior experience operating and/or evacuating through a roof hatch, whereas participants in the study conducted by Pollard and Markos (2009) had prior knowledge on opening emergency exits. Inability to apply an adequate amount of push force to disengage the locking mechanism was the reason the roof hatch could not be opened. Additionally, in a post-accident scenario, other factors may further impede the ability of young occupants to open and exit via the emergency escape roof hatch. As shown in Table 4, the mean evacuation flow rate from the roof hatch for children in the second grade was one child per minute lower than the flow rates of children in the first grade. This could be due to the larger size of children evacuating through the roof hatch, or a result of a limited sample size.

Cognitively, the children in the study were representative of the overall population. Their basic reading skills on the sight word test was as expected. However, their reading performance on the emergency-related words that were taken from school bus roof hatches was quite poor. The word with the highest accuracy level, *push*, was only read correctly by 54% of the participants. Participants were unable to read the words, despite the fact that they are in the English lexicon. For example, the word *turn* is a high frequency word (89,684 in the HAL database, average frequency of 10,778; Balota et al., 2007), but only 26% of participants could read it. The participants, however, were fairly capable of defining the words. This result, plus the finding that the majority of participants could act out the instructions when they were read to them, suggests that K-2 children are capable of understanding how to operate the roof hatch. However, the most direct test of the participants' abilities was the phrase reading task in which participants had to read the roof hatch instructions and act them out. Very few children were capable of doing so. For the participants that could read the instructions but not accurately carry them out, there were three common mistakes. First, participants would physically turn their bodies around when they read the phrase, "*Turn then push knob to open"*. Most children were capable of correcting that mistake once the context was established. A second error was that children would fail to complete both actions. Most frequently they would act out turning the knob but then fail to push the door open. Finally, children would pull rather than push the knob.

5. Practical applications

Some research on the ability of children to follow directions has been completed that may provide insight into steps that could be taken to improve a student's ability to follow emergency directions (Kaplan & White, 1980; Engle et al., 1991). Unfortunately, the majority of this work has used spoken instructions rather than written instructions, like those on a school bus hatch. Kaplan and White (1980) showed that children in grades K-2 could follow spoken directions without any errors only when there was a single behavior required. The written instructions on the roof hatch require two behaviors (turn and push). However, these directions are complicated by the need to qualify that it is the hatch's knob that should be turned and pushed. Simplification of the instructions would appear to be useful for young children. Alternatively, a system that could provide auditory instructions for children or automate the process entirely in the case of an emergency may improve the likelihood that a student may be able to exit safely.

Existing research on school bus safety instruction suggests that although training is provided to some children, the training is on topics related to preventing injuries and accidents when getting on and off the bus, and bus riding safety (Lartey et al., 2006). There was no indication in the survey that teachers provided instruction on emergency procedures. Further, the study showed that only 17 out of the 37 states surveyed mandated school bus safety education for children in elementary school only 39% of teachers knew that school bus safety education was mandated. For teachers that do teach bus safety, they spend on average over 90 min on safety education (Lartey et al., 2006). A simple intervention to improve this training would be to include an educational unit on emergency-related words during reading instruction.

Training students on how to open the roof hatch is another practical modification that can be made to current school bus safety practices. Research on enactment has shown that when children enact something, their memory of it is superior to other forms of encoding (Cohen, 1989). Periodic reminders or reenactments can maintain the memory for months at a time in children as young as 18 months old (Hudson & Sheffield, 1998). Therefore, the training should involve having the children act out the process with reminders at least once a semester.

Further evaluation of the force and design requirements specified by FMVSS No. 217 for all school bus emergency exits including the rear emergency door and emergency windows are also recommended. Establishing age-specific requirements for operating emergency exits may also improve the overall evacuation process. For instance, the Federal Aviation Administration (FAA) has requirements for passengers sitting in an emergency exit row to ensure they are able to operate the exit in an emergency (FAA, 1990). Based on the results of the study, requiring older children to be seated near a roof hatch may improve the likelihood of successful hatch operation.

6. Limitations

Several limitations were associated with the study. The physical and cognitive capabilities of children to operate the roof hatch were assessed separately. Performing a combined assessment of the physical and cognitive capabilities of children would potentially have been beneficial in identifying the interactive importance of these factors in the operation of the school bus roof hatch. We recommend future studies consider these interactions. To ensure participant safety, gym mats were stacked on the outside portion of the roof hatch opening to provide a softer landing surface during the self-extrication portion of the study. This may have affected the posture of the students as they self-extricated through the roof hatch since the drop in elevation was significantly lessened outside the roof hatch. Due to time restrictions, the ability of children to operate the roof hatch opening without instruction was not studied. Only one type of roof hatch was tested during this study, there are different types of roof hatches used on school buses that require different operation methods to open. Studying the abilities of children to operate different types of roof hatches would provide a more holistic understanding of the operability of roof hatches. Furthermore, the flow rate through the exit may be different in a post-accident scenario due to injuries, fear, and other environmental stressors. Further research should also be conducted on different types of roof hatches and identifying countermeasures that could help improve self-extrication through roof hatches. The results presented in this study are primarily based on a correlation analysis assessing the relationship between the physical and cognitive capabilities of children and their ability to operate and self-extricate through the school bus roof hatch. Additional research must be conducted to evaluate the cause-and-effect relationship between these variables.

7. Conclusions

While school bus roof hatches serve as important egress routes in a rolled-over school bus evacuation scenario, the design of these emergency exits does not reflect the physical and cognitive abilities of K-2 children. In any instance where the school bus driver is incapacitated or unable to assist in the evacuation process, it is the sole responsibility of the children to initiate the evacuation process until further help arrives. The usability of emergency exits has a great impact on the time available for successful evacuation. Results of this study suggest that further evaluation of FMVSS No. 217 as an established standard for emergency school bus roof hatches is warranted. These findings serve as a critical first step in identifying mismatches between existing emergency roof hatch design specifications and the capabilities of the youngest school bus riders.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ssci.2018.08.026.

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