MODELLING AND SIMULATING AGE-DEPENDENT PEDESTRIAN BEHAVIOURS WITH AN AUTONOMOUS VEHICLE

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ABSTRACT

In shared spaces, autonomous vehicles (AVs) will have to move efficiently and safely, without normal road signage, and with other users such as pedestrians, cyclists and drivers. To achieve this, AVs need to anticipate the behaviours of other road users in order to adapt their navigation accordingly. This paper focuses on age-related pedestrian behaviours with an autonomous vehicle. Looking at age as one of the main factors determining behaviour, a literature review is conducted. The results are used to integrate age-dependent pedestrian behaviours into a model for simulating more realistic pedestrian behaviours in shared spaces with an AV.

INTRODUCTION

In recent years, autonomous vehicles (AVs) have been tested on roads shared with other users e.g. pedestrians, cyclists, and drivers (McAslan et al. 2021). In such environments, AVs adapt their navigation according to the traffic regulations such as stopping at a red light. Nevertheless, in the near future, AVs will increasingly have to navigate in shared spaces. A shared space is a space without signage, where pedestrians and AVs have no physical definition of how to share the space (Hamilton-Baillie 2008). In such spaces, all users must adapt their trajectory so that everyone can navigate safely and efficiently. However, AVs are currently not designed to operate in these potentially crowded spaces. To have safe and efficient navigation in shared spaces, i.e. avoiding accidents and unnecessary preventive stops, AVs need to anticipate pedestrians' behaviours, in much the same way as human drivers. When developing AV navigation systems suitable for shared spaces, testing such systems in real-life can be dangerous and complicated because of the risk of accidents and high deployment costs. A simulated environment offers a safe and cost-effective alternative to real-world experimentation for the first tests of navigation systems. Modelling and simulating pedestrian behaviours are key aspects of such a simulated environment. Recent models of pedestrian behaviours are mainly based on observations of standard pedestrians, with adult behaviours (Helbing & Molnar 1995, Moussaïd et al. 2009, 2010, Kim et al. 2015, Van den Berg et al. 2008). In shared spaces, AVs will interact with a more heterogeneous population and pedestrian behaviours will be more varied - e.g. a child running or an elderly person walking more slowly than a younger adult. While many research studies have reported observations on age-related pedestrian behaviours with cars, these age-related behaviours have not been included in a pedestrian-car interaction model. An exception is the age-dependent behavioural model by Kaup et al. (2008). The authors modified the social force model (SFM), which is widely used in crowd simulation, to take into account age differences (children, adults and elderly people) in pedestrian behaviour. However, their SFM modifications rely only on assumptions, made without observations or literature sources. Moreover, the validation was only based on visual comparisons with night-recorded video data. Our work overcomes these problems and advances current work by basing behaviours on findings from the literature and by conducting a thorough validation of the results.

This paper presents an agent-based model (ABM) that considers age-dependent pedestrian behaviours with an autonomous vehicle. The proposed model extends an ABM and a simulator named SPACiSS (Simulation of Pedestrian and Autonomous Car in Shared Spaces) that simulates pedestrians in shared spaces with an AV (Prédhumeau 2021, Prédhumeau et al. 2022*a*). The original ABM and simulator integrate the visual perception and attention of pedestrians and the concept of personal space. SPACiSS models individuals and social groups of pedestrians, such as friends, couples, coworkers and families, as well as, interactions with a car in shared spaces. Based on empirical observations, pedestrian-vehicle interactions are modelled by combining the SFM with a pedestrian decision model. The model was calibrated and validated through a quantitative comparison of the simulated trajectories with ground truth trajectories (Prédhumeau et al. 2022*a*). However, this model and simulator only include adult

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pedestrians. Other ages must be modelled in order to be more representative of real pedestrian behaviours.

The aims of this paper are: 1. to review specific pedestrian behaviours associated with age in the literature, and 2. to integrate these behaviours into the existing model, and implement and test them in the simulator. To answer these aims, we used an iterative approach consisting of 4 stages: a literature review, behavioural modelling, an implementation of the behaviours in the simulator, and verification tests of the new behaviours.

LITERATURE REVIEW

In order to identify new behaviours to add to the model (Prédhumeau 2021, Prédhumeau et al. 2022*a*), we conducted a literature review. Relying on a literature review allowed us to overcome the time and cost issues associated with real experiments.

Methodology

First, we conducted a literature review focusing on the age of pedestrians since this is an important discriminating factor for behaviours. The purpose of this literature review was to extract specific age-dependant behaviours. We focused on three populations: children, adolescents and elderly people - without major cognitive or physical problems. We used two general scientific libraries: ScienceDirect and HAL, as well as Google Scholar and ResearchGate. The research was multidisciplinary, drawing upon works in computer science, social science, accidentology, and psychology. We combined terms "children" OR "adolescent" OR "elderly" AND "pedestrian" with the general term "behaviour" OR with the terms describing common pedestrian behaviours (i.e. "walking speed" OR "time gap" OR ("phone" OR "music")*"distraction" OR "decision time" OR "reaction time"). The searches were initially conducted using the terms "autonomous vehicle" AND/OR "shared space", then without them to include normal vehicles and spaces. We consulted and retained 25 articles dating from 1993 to 2021. The articles have been selected by the relevance of the method and the results. For example, an article with real-life experimentation was deemed more useful than an article using virtual reality.

Findings from the literature review

The papers were analysed to identify the actions and behaviours pedestrians perform and the related age categories. The terms identified as behaviours were:

1) "(time to) cross a road",
2) "using phone",
3) "listening to music",
4) "using headphones",
5) "texting",
6) "decision time"
7) "running"

Finally, seven behaviours were extracted - five behaviours depending on age, and two general behaviours that looked at the effect of distraction on the walking speed (Table I):

1) Mean walking speed: mean walking speed for the population (Stansfield et al. 2006, Van Hamme et al. 2016, Samson et al. 2012, Deluka-Tibljaš et al. 2021, Leung et al. 2021, Jiang et al. 2021, Bosina & Weidmann 2017, Willis et al. 2004, Huguenin-Richard et al. 2015, Oxley et al. 2005, Ishaque & Noland 2008),
2) % of the population running: percentage of population likely to run in front of a vehicle when the situation is ambiguous and the choice is to stop or run (Cloutier et al. 2014, Zeedyk et al. 2002),
3) Decision time: time needed to take the decision to cross the road when a vehicle is approaching (Bucsuházy & Semela 2017, Rasulo et al. 2020, Lynn & Ja-Song 1993, Whelan 2008, Oxley et al. 2005),
4) % distracted by texting: percentage of the population texting on a phone during road crossing (Focant 2021, Nasar & Troyer 2013, Zhou et al. 2019, Russo et al. 2018, Gitelman et al. 2019),
5) % distracted by music: percentage of the population listening to music with headphones during road crossing (Focant 2021, Nasar & Troyer 2013, Zhou et al. 2019, Russo et al. 2018, Gitelman et al. 2019),
6) Effect of texting on walking speed: effect of using a phone for texting on walking speed (Thompson et al. 2013),
7) Effect of listening to music on walking speed: effect of listening to music with headphones on walking speed (Thompson et al. 2013).

Using categories that cover a wide range of ages, e.g. children, adults and the elderly, is unsatisfactory because behaviours vary considerably within each category. Therefore, children are divided into four groups and the elderly into two groups to better reflect the behaviours variations. This age categorization corresponds to that of the consulted articles. The walking speed of children gradually increases with age with a significant increase for the 8-11 years age group (Stansfield et al. 2006, Van Hamme et al. 2016, Samson et al. 2012, Deluka-Tibljaš et al. 2021, Leung et al. 2021, Jiang et al. 2021). Conversely, the walking speed of the elderly decreases with age, notably after 70 years old (Bosina & Weidmann 2017, Willis et al. 2004, Huguenin-Richard et al. 2015, Oxley et al. 2005, Ishaque & Noland 2008). Moreover, children take more time to decide to cross a road than adults (Bucsuházy & Semela 2017, Rasulo et al. 2020, Lynn & Ja-Song 1993, Whelan 2008). The decision time is the longest for the elderly (Oxley et al. 2005). Adolescents are the age group that uses their phones the most and listens to the most music (Focant 2021, Nasar & Troyer 2013, Zhou et al. 2019, Russo et al. 2018, Gitelman et al. 2019). Thus, adolescents are more likely to be distracted and have their behaviour altered by using their phones or listening to music (Nasar et al. 2008).

From this literature review the behaviours, which have been summarized in Table I, have been added to the model and simulator.

MODELLING

Definition of 6 agent types

The original model did not differentiate between the behaviour of each type of pedestrian e.g. a child or an elderly person had the same reaction time and walking speed as an adult. From the literature review, children aged 8 to 11 have a

TABLE I: Behavioural data from the literature depending on pedestrian age

	Adults (reference group)	Children				Adolescents	Elderly	
Age (years)	19-59	1-3	4-5	6-7	8-11	12-18	60-70	>70
Mean walking speed (±std) (m/s)	1.34 (±0.26)	0.40 (±0.35)	0.44 (±0,35)	0.47 (±0,35)	1.23 (±0,31)	1.34 (±0.26)	1.29 (±0.24)	1.05 (±0.24)
% of the population running	73	**n/a**	63.5	63.5	**n/a**	**n/a**	27	27
Decision time (s)	0.57	**n/a**	0.87	0.87	0.85	0.67	0.88	1.45
% distracted by texting	13.2	**n/a**	**n/a**	1.6	5.7	15.25	0.25	0.25
% distracted by music	5.7	**n/a**	**n/a**	1.3	1.3	9.75	0.25	0.25
Effect of texting on walking speed (m/s)	-0.19	**n/a**	**n/a**	**n/a**	**n/a**	-0.19	-0.19	-0.19
Effect of listening to music on walking speed (m/s)	+0.54	**n/a**	**n/a**	+0.07	+0.07	+0.07	+0.07	+0.07

n/a is for the case of missing or irrelevant data.
The - symbol indicates a decrease in walking speed, whereas the + symbol indicates an increase in walking speed.

significantly different walking speed than children aged 1 to 7. The same observation is made for the elderly between 60 and 70 years and >70 regarding the walking speed and decision time. Thus, we retained six types of agent (in brackets the corresponding years in Table I):

- Agent (Adults, 19-59 years old),
- Child (1-7 years old),
- Preadolescent (8-11 years old),
- Adolescent (12-18 years old),
- Elderly (60-70 years old),
- Old elderly (> 70 years old).

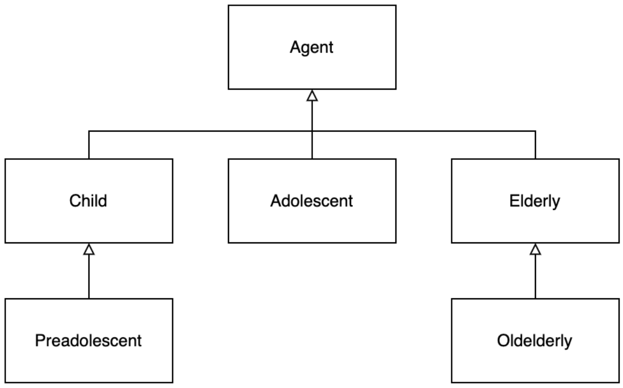

Fig. 1: A simplified UML diagram of class inheritance

Application of the inheritance concept

For modelling, we used multi-level inheritance. Inheritance allows a subclass to inherit the methods and properties of its superclass while being able to modify these methods and apply its own methods. One superclass, the Agent class, includes the methods and specifications of adult pedestrians. Then, three subclasses inherit from Agent: Child, Adolescent, and Elderly. Two other subclasses are added: Preadolescent inheriting from Child and Oldelderly inheriting from Elderly (Figure 1). For example, a Preadolescent (8-11 years) inherits the attributes and methods from the Child class and from the Agent class with Child modifications.

Furthermore, inheritance allows the agent groups that have **n/a** data to use the values from their superclass. For example, the running percentage of a Preadolescent is inherited from the Child class while the running percentage of an Adolescent is inherited from the Agent class.

Behavioural modelling

The original model is detailed in (Prédhumeau 2021, Prédhumeau et al. 2022*a*). To bring the model closer to real behaviours for all classes, several behaviours were modified. We added a decision time to the agents, and modified the running decision and the distraction caused by texting and listening to music.

When a pedestrian interacts laterally with the AV and the crossing order is unclear, the pedestrian hesitates. In the original model, pedestrians had a 50% chance of running or stopping. We changed this percentage to use the proportion of pedestrians affected by the behaviour according to their age group. For example, an Elderly has a 27% chance of running when a vehicle is approaching while an Adult has a 73% chance of running. For a Preadolescent, the percentage is 63.5% and is inherited from the Child class (Algorithm 1).

Algorithm 1: Running decision for a Preadolescent

```
begin
    // AV is approaching
    // preadolescent is not stopping and not running,
       i.e. is hesitating

    runningDecision = random number on [0;100]
    if runningDecision <= 63.5 then
        decide to run
    else
        decide to stop
    end
end
```

In the original model, each pedestrian is assigned a random distraction level between 0 and 1, which varies periodically and modifies the agent's perception and attention distances. During the simulation, each agent can thus be temporarily distracted. The distraction level was changed to be the proportion of pedestrians affected by texting on the phone and by listening to music. The distraction is no longer a single variable, but the result of two parameters: texting and listening to music. For example, an Elderly has a 0.25% chance of being distracted by texting and a 0.25% chance of being distracted by listening to music, while for Adults these percentages are 13.2% and 5.7% respectively. For Preadolescents, being distracted by texting is 5.7% and 1.3% for listening to music, which is inherited from the Child class (Algorithm 2). We also differentiated between distraction by texting or music regarding their effect on walking speed.

Algorithm 2: Variation of distraction and effect on walking speed for a Preadolescent

```
begin
    // preadolescent is not distracted
    textingDistraction = random number on [0;100]
    musicDistraction = random number on [0;100]

    // is not distracted by texting or by music
    if textingDistraction > 5.7 and
     musicDistraction > 1.3 then
        walkSpeed = walkSpeed
    else
        // is distracted by texting and not by music
        if textingDistraction <= 5.7 and
         musicDistraction > 1.3 then
            walkSpeed = walkSpeed – 0.19
        else
            // is distracted by music and not by texting
            if textingDistraction > 5.7 and
             musicDistraction <= 1.3 then
                walkSpeed = walkSpeed + 0.07
            else
                // is distracted by texting and by music
                if textingDistraction <= 5.7 and
                 musicDistraction <= 1.3 then
                    walkSpeed = walkSpeed + 0.12
                end
            end
        end
end
```

In Algorithm 2, the values -0.19 and +0.07 correspond respectively to the effect of texting and listening to music on the walking speed for all agents. The value +0.12 corresponds to the addition of the effects of texting and listening to music on walking speed for all agents.

For the two algorithms, the number used in the *if* test is the observed percentage of the population that shows the considered behaviour. The approach is to select a random number between 0 and 100 and compare it with the percentage of the population. If the random number is less or equal to the percentage of the population, the pedestrian is considered as being in the percentage - i.e. he will apply the behaviour. If the random number is greater than the percentage of the population, the pedestrian will not apply the behaviour.

IMPLEMENTATION AND TESTS

Implementation in the SPACiSS simulator

The model has been implemented in C++ in the SPACiSS simulator. The SPACiSS simulator is based on Pedsim_ROS, which is a crowd simulator using the ROS robotic framework. SPACiSS can be used to test autonomous navigation systems in virtual crowds before tests with real pedestrians. The movements of the simulated AV can be controlled by an external navigation system, and simulated pedestrians consequently react in real-time. The code is open source and the original SPACiSS version is freely available from (Predhumeau et al. 2022*b*). The proposed adaptation is available at https://github.com/OphelieJo/SPACiSS/ on the "noetic" branch.

To implement the proposed model, we used C++ inheritance and adapted or added several methods and attributes (Figure 2).

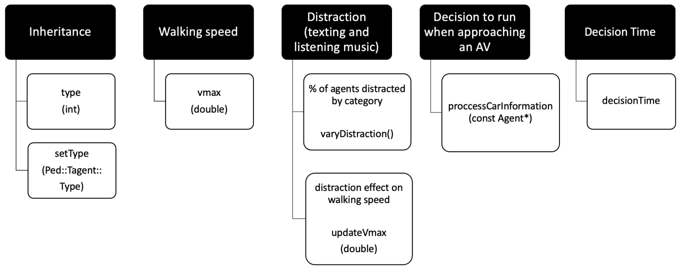

Fig. 2: Modified attributes and methods and their implementation in the simulator

The type of agent is managed by a *setType* method taking the age category as a parameter. The *setType* method fixes the attribute values of the agent depending on its type, e.g. the preferred walking speed, probability of distraction by texting or music, and decision time. The preferred walking speed is drawn from a normal distribution with means and standard deviations from the literature (Table I). The walking speed changes during the simulation depending on the interaction with other agents, distraction or the decision to run.

The subclass implementations of the methods *varyDistraction*, *updateVmax* and *processCarInformation* vary only in the parameters values used. We did not overwrite these methods in each subclass. Instead, we used class constants to model the variables with values that are specific to each pedestrian class, i.e. the running percentage, decision time, percentage of pedestrians distracted by texting and distracted by music.

Simulation videos, showing the different types of pedestrians, are available at https://doi.org/10.5281/zenodo.7855146.

Implementation testing

Tests were run to check if the simulation outputs were consistent with the literature observations. Since the model is stochastic, each test scenario was simulated between 10 and 25 times in order to smooth out the stochasticity and calculate average outputs. The purpose was to compare the mean value found in the literature with the mean simulation output (except for the verification of the agent type). Table II shows the test scenarios and results. The difference between test results and literature data can be explained by the limited number of tests and the resulting randomness. A next step will be to confirm the results using a hundred simulations. As shown in Table II, we changed four parameters during testing:

1) the type and the number of pedestrians,
2) the presence of the AV,

3) the presence of distraction,
4) the walking speed.

The verification of agent types was done by adding a test variable in each class, indicating the name of the class, i.e. "preadolescent" when the test was run with preadolescent pedestrians.

The verification scenarios for the walking speed test were composed of one pedestrian of each type. The AV was not present, the positions of pedestrians were fixed and the distraction was disabled. This was done to avoid speed variations caused by pedestrian interactions with AV and others pedestrians and by distraction. The test results show that the walking speed for each type matches well with the data in the literature. For example, for Agent and Adolescent, the walking speed should be between 1.08 and 1.60 m/s. The mean walking speed from the test is 1.41 m/s for Agent and 1.20 m/s for Adolescent which matches literature data. Similarly, for all the other agent types, the results are within the literature range.

The verification scenarios for texting and music distractions were composed of one pedestrian of each type for each test. The AV was not present and the positions of pedestrians were fixed. The simulated percentage of agents texting and listening to music, and the simulated differences in walking speeds depending on the distraction are very close to the literature data. For example, for Agent, texting and music distractions should be respectively 13.2% and 5.7%. The test results are respectively 8.67% and 4.30%. Regarding the effect of the distraction on the walking speed, the effects of distraction only by texting and only by music should be respectively -0.19 and +0.07 m/s. The test results are close, i.e. -0.13 m/s for texting and +0.04 m/s for listening to music.

The verification scenarios for testing the running decision were composed of one pedestrian of one type for each test. The running decision is dependent on the presence of the AV, so the simulated AV was present moving along a straight path at constant speed. To avoid pedestrian speed variations unrelated to the interaction with the AV, the distraction was disabled. For the test conditions to be the same for each type, the position of the pedestrian relative to the AV was always the same at the start of the test and the walking speed was fixed at 1.30 m/s. The percentages of running pedestrians found in the simulation are similar to the literature data for each class. For example, for Agent (including Preadolescent and Adolescent), the literature notes 73% of pedestrians running and the test result is 68%.

The verification scenarios for the decision time were composed of one pedestrian of one type for each test. The decision time is dependent on the presence of AV, so the simulated AV was present. The distraction was disabled to avoid the variations of speed unrelated to the interaction with the AV. The simulated results show that the decision time for each type is the same that in the literature data. For example, for Agent (including Adolescent), the decision time from the literature is 0.66 s and the test result is 0.66 s.

For all tests, the average simulated values were similar to the literature reference values and followed the same trends. The small differences are due to the reduced number of tests and will be further investigated in future work.

CONCLUSION AND FUTURE WORK

This work extended the SPACiSS model and simulator to make simulated pedestrian behaviours more realistic by diversifying the range of modelled behaviours. The overall goal is to be able to better anticipate pedestrian behaviour in order to design better AV navigation systems.

A literature review allowed us to identify pedestrian behaviours that vary with age. Important differences between the behaviours of different age groups were found. The original pedestrian model was extended with the new age-related behaviours, which were implemented in the SPACiSS simulator.The implementation was tested to check that the outputs corresponded to the literature data. The verification results showed that the behaviours that are consistent with observations across age groups. The integration of these behaviours into the model and simulator can provide a more realistic virtual test environment to improve AV systems before real-world testing.

Despite increasing the realism of simulated behaviours, this work has some limitations. First, we relied exclusively on data from the literature, and did not use a dedicated dataset. We aggregated findings from several sources when possible but sometimes had to rely on a single source when data was scarce, e.g. data on the effect of texting and listening to music on walking speed. Moreover, data on interactions between pedestrians and AVs in shared spaces is also scarce. Therefore, we relied mainly on data from studies of pedestrian-vehicle interactions on conventional roads, i.e. roads with signage and differentiated spaces for pedestrians and vehicles. For example, the decision time and the running percentage are based on data about crossings for conventional roads. Due to the lack of data on AVs in shared spaces, we assumed that pedestrian behaviour in shared spaces with AVs will be the same as with cars on conventional roads, which is not necessarily the case. An estimation bias could then exist. It would be useful to quantify this bias and its impact.

Future work could be conducted to address these gaps. The literature review revealed that while some pedestrian behaviours are well studied, e.g. walking speed, other behaviours require further attention, e.g. the decision time or running decision of adolescent pedestrians. To address the lack of data on pedestrian behaviour in shared spaces, future work could set up a fictitious shared space, e.g. on a university campus. This type of study has already been carried out but was limited to adults only (Yang et al. 2019). We focused on age as a determining factor of behaviour and did not consider other aspects such as people with visual, auditory, or physical problems. Future work will focus on extending the model and simulator with behaviours specific to these populations. Additionally, SPACiSS focuses exclusively on pedestrians. In a real shared space, the AV will also be confronted with other forms of transport, e.g. bicycles, and other autonomous and non-autonomous vehicles. Future work will extend SPACiSS with these particular road users. Recent studies have shown that the elderly could be less comfortable with AVs than other age groups (Rad et al. 2020, Hulse et al. 2018), which might influence their behaviour. The model could be further extended to take this into account. Finally, a sensitivity analysis of the model to the input values should be performed as well as validation with other data sources, such as real-life videos.

TABLE II: Criteria and test scenario for each modification of the model

	Walking speed	**Texting and music distraction**					**Running decision**	**Decision time**
Method or attribute tested	double vmax	void *varyDistraction()*	void *updateVmax(double)*				void *processCarInformation(Agent)*	double decisionTime
Agents specifications	Crowd of pedestrians of 1 type	Crowd of pedestrians of 1 type	1 pedestrian of each type				1 pedestrian of 1 type	1 pedestrian of 1 type
Presence of AV	No	No					Yes	Yes
Distraction	Disabled	Enabled					Disabled	Disabled
Walking speed	Set according to agent type	Set according to agent type					Set to 1.30 m/s for all	Set according to agent type
Test method	Average walking speed by type (in m/s)	Average % of texting distraction by type	Difference of speed between distracted by texting and not distracted	Difference of speed between distracted by music and not distracted	Difference of speed between distracted by texting and music and not distracted	Difference of speed between distracted by texting + not distracted by music	Average % of pedestrians running when crossing by type	Comparison of the decision time (in s) with the reference value for each test
Reference value	Agent: 1.34±0.26 Child: 0.43±0.35 Preado.: 1.20±0.31 Ado.: 1.34±0.26 Elderly: 1.29±0.24 Oldeld.: 1.05±0.24	Agent: Texting 13.2% Music 5.7% Child: Texting 1.6% Music 1.3% Preado.: Texting 5.7% Music 1.3% Ado.: Texting 15.25% Music 9.75% Elderly: Texting 0.25% Music 0.25% Oldeld.: Texting 0.25% Music 0.25%	-0.19	+0.07	+0.12	+0.26	Agent: 73% Child: 63.5% Elderly: 27% Oldelderly: 27%	Agent: 0.66 Child: 0.87 Preado.: 0.85 Elderly: 0.88 Oldelderly: 1.45
Simulated result	Agent: 1.41 Child: 0.43 Preadolescent: 1.21 Adolescent: 1.20 Elderly: 1.18 Oldelderly: 1.01	Agent: Texting 8.67% Music 4.30% Child: Texting 1.14% Music 0.95% Preado.: Texting 4% Music 1.05% Ado.: Texting 10.02% Music 6.64% Elderly: Texting 0.16% Music 0.22% Oldeld.: Texting 0.20% Music 0.13%	-0.13	+0.04	+0.10	+0.20	Agent: 68% Child: 66% Elderly: 26% Oldelderly: 26%	Agent: 0.66 Child: 0.87 Preado.: 0.85 Elderly: 0.88 Oldelderly: 1.45

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