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Central tendency in space perception varies in development and is altered in human-robot interactive tasks.

Alessandra Sciutti, Andrea Del Prete, Lorenzo Natale, Giulio Sandini, Monica Gori
Robotics, Brain and Cognitive Sciences Dept.
Istituto Italiano di Tecnologia
Genoa, Italy

David Burr
Dipartimento di Psicologia
Università degli Studi di Firenze
Florence, Italy

I. Introduction

A fundamental principle in time perception is the so-called central tendency: reproductions of time intervals regress to the mean value of the previous stimuli distribution [1, 3-4]. Therefore, the estimate of sample duration differs depending on the distribution from which it is drawn, i.e. its statistical context. Central tendency is not just the consequence of a decrease of attention in a repetitive task, but rather optimizes temporal reproduction by minimizing the total error, which comprises both the accuracy and the variance of the responses [1, 4]. This strategy compensates for low sensory resolution by sacrificing veridicality, as it takes into account the statistics of previous stimuli rather than just the current stimulation. To explain the benefit of applying this strategy, we can propose an analogy with an everyday judgment. Consider the task of estimating the real dimension of an object (e.g. a car) by looking at its picture. If we were to evaluate the object size only on the basis of the current visual information, a car would be misperceived as a few cm long. On the contrary, usually our estimation is based on an internalized average measure, derived from a statistics of all the cars that we have seen in the past. The ability to take into account environmental statistics during perception could be advantageous also on a robotic platform. However, from a practical point of view, it is important to evaluate whether this optimization approach could be always beneficial and, if not, in what circumstances would it be more advantageous. In particular, it is interesting to investigate how this mechanism develops during childhood. Recent Bayesian models of the phenomenon in human adults [1, 4] have shown that the central-tendency strategy is beneficial only when perceptual judgment is imprecise and that the entity of the regression to the mean depends strongly on the precision with which such judgment can be made.

In this study we evaluated whether other factors can influence the feasibility of the central tendency in perception, to establish when it would be appropriate to endow the robot with this optimization mechanism. In particular we considered the relevance of three factors in determining the adoption of the central tendency in humans:

The quantity to be judged, moving from time to space perception. The idea of studying space rather than time perception derives from a hypothesis put forward by Hollingworth already in 1910 [3]. According to his view, the perceptual principle of central tendency should apply also to other sensory judgments rather than time, although recent studies have been focused only on the latter. Therefore, in this work we evaluated whether central tendency generalizes also to space perception.

The developmental phase, as different strategies could be beneficial at different phases of the development. Although the central tendency mechanism is a gold standard in perceptual judgments in adults, how this strategy develops with age is still unknown. On the one hand, in children sensory precision is usually lower than in adults. Therefore, a strategy aimed at minimizing the variance of sensory judgments could be particularly beneficial at younger ages. On the other hand, for the developing brain it could be fundamental to formulate estimations as veridical as possible, at the expenses of production variance, so that – by trial and the feedback of the error – children could develop the ability to produce accurate judgments. Hence, a Bayesian model aimed at minimizing the total error by reducing veridicality could be adopted only later in the development. This is what happens for instance in the development of sensory fusion: before adopting the Bayesian

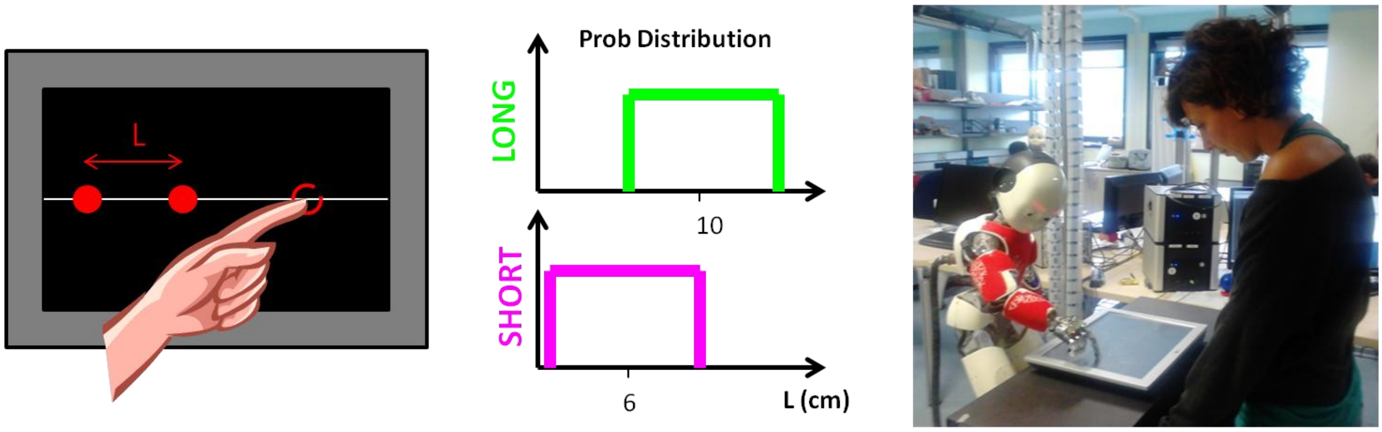

Fig. 1. Schematic representation of the task and of the stimuli distributions in the LONG and SHORT conditions. On the right, picture of the interactive task.

optimization of a multimodal judgment, the brain needs to calibrate the single modality estimation by using the more reliable sense [2]. Only when the calibration has occurred, the adult-like multimodal Bayesian integration occurs. In this study we evaluated the developmental trend of the central tendency mechanism in children between 7 and 14 years of age.

Interactive vs. not interactive context, as a judgment finalized to an interaction might need to obey to different constraints than a judgment per se. Even in adults, the central tendency mechanism could sometimes be not beneficial. In particular, when we move from perceptual tasks to interactive tasks, accuracy (or veridicality) could acquire a higher relevance than robustness to perceptual noise. Indeed, an inaccurate evaluation of the amplitude of the arm movement of another agent passing an object could imply a failure of the cooperative task. Hence, it could sometimes be inappropriate to sacrifice accuracy for minimizing the total error. We performed an interactive spatial task with the humanoid robot iCub as a co-actor to assess whether central tendency is normally adopted by adults in interactive scenarios too.

The results of this study can give insights on whether it is really relevant (and under which conditions it is appropriate) to implement the central tendency optimization mechanism in a robotic device.

II. METHODS

In this study we tested the central tendency strategy for space estimation in adults, in both a perceptual task (6 subjects) and an interactive task (7 subjects). Moreover, we tested children ranging from 7 to 14 years of age (a total of 77 subjects divided into five age groups) in the first task, to evaluate the development of the phenomenon. In the developmental study we used such a larger number of subjects, (in traditional studies with adults the sample is of 6 subjects [1, 4]) because children data are usually characterized by a high variability.

In the perceptual task, on each trial, subjects were presented with two subsequent flashes of light (red disks of 1 cm of diameter, each flash lasting 400 ms) positioned along a visible straight white line crossing the whole screen at its middle height. The first flash was located at a variable distance from the left border of the screen (0.5-3.5 cm, randomly selected). On its disappearance, a second disk appeared at a variable distance from it. Subjects were requested to touch a point on the straight line in order to reproduce, with respect to the second disk, the distance between the first and the second disk. After the touch, a red disk appeared to indicate where the subject had pressed the screen. No feedback was provided. Each new trial started after the experimenter's button press, with the first light appearing after 500 ms. Each subject participated in two sessions: a SHORT condition, in which the spatial distance between the first two disks ranged from 2 cm to 10 cm, and a LONG condition, in which the presented distances ranged from 6 cm to 14 cm (see Fig.1). To avoid interference between the two contexts the two conditions were tested in two different days. The order of the sessions was randomized between subjects. Each condition was characterized by 11 different sample intervals (separated by 0.8 cm each), each of which was presented 8 times, yielding to a total of 88 trials per subject per condition.

In the interaction task the stimuli were similar, but the task was presented as a collaborative game. The humanoid robot iCub pressed the touch screen in two different points in sequence and the subjects had to complete its action by

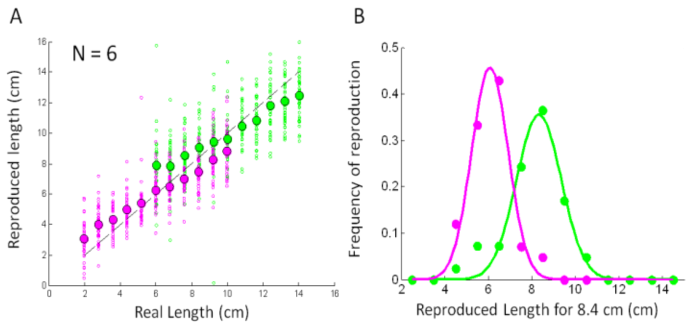

Fig. 2. A) Reproduced lengths as a function of stimulus length for two stimulus ranges (short – magenta, long – green). B) Reproduction distribution of visual stimuli for the stimulus 8.5 cm during sessions where stimuli were drawn from the short or the long contexts (same color coding as Fig. 2A).

touching a third point to reproduce the distance shown by the robot. iCub performed a human-like approximate minimum-jerk movement (6) and exhibited a naturalistic gaze behavior (5), with the eyes looking towards the pointing target before the movement completion and then fixating the human subject when his/her turn started. The stimuli presentation was slower than in the perceptual condition, with the mean robot velocity being constant across trials (average hand speed of about 0.1 m/s). The use of the robotic platform iCub guaranteed a complete control over the statistics and the timing of the stimuli presentation, to allow for a comparison with the computerized perceptual task. Before each experimental session, a calibration was performed to register the frames of reference of the robot and the touch screen. The distances presented by the robot were not sampled in 11 intervals but were drawn from the same uniform distributions that we used in the perceptual task, as in (4).

III. RESULTS

A. *Central tendency in the perception of space*

The results in Fig. 2 show that the phenomenon of central tendency is present in adults also for space perception. The average reproduced lengths (larger dots in Fig. 2A) do not correspond to the real stimulus amplitude (the data would lie on the identity line in such case), but tend to the mean value of the corresponding stimulus distribution (6 cm and 10 cm for the magenta and green data points, respectively), lying on flatter lines. The central tendency can be quantified by the regression index, i.e. the difference in slope between the best linear fit of the reproduced lengths and the identity line. This index varies from 0 (veridical performance) to 1 (complete regression to the mean) and was on average 0.35 ± 0.08 (Standard Error of the Mean, SEM). The central tendency is even more clearly depicted in Fig. 2B, where the distribution for the reproductions of the stimulus of 8.5 cm depends strongly on the sample range from which it was drawn, tending towards a shorter mean length for stimuli in the short range (magenta) and a longer mean for stimuli in the long range (green).

B. *The development of the central tendency mechanism*

As depicted in Figure 3A, during development a clear change is observed in the reproduction of spatial stimuli. Interestingly a developmental trend seems to be active until 13 years of age, with a progressive increase in children's accuracy shown by the decrease of the regression index. Indeed, the regression index decreases substantially with age, reaching adult-like values around 11-13 years of age (see Fig. 3B).

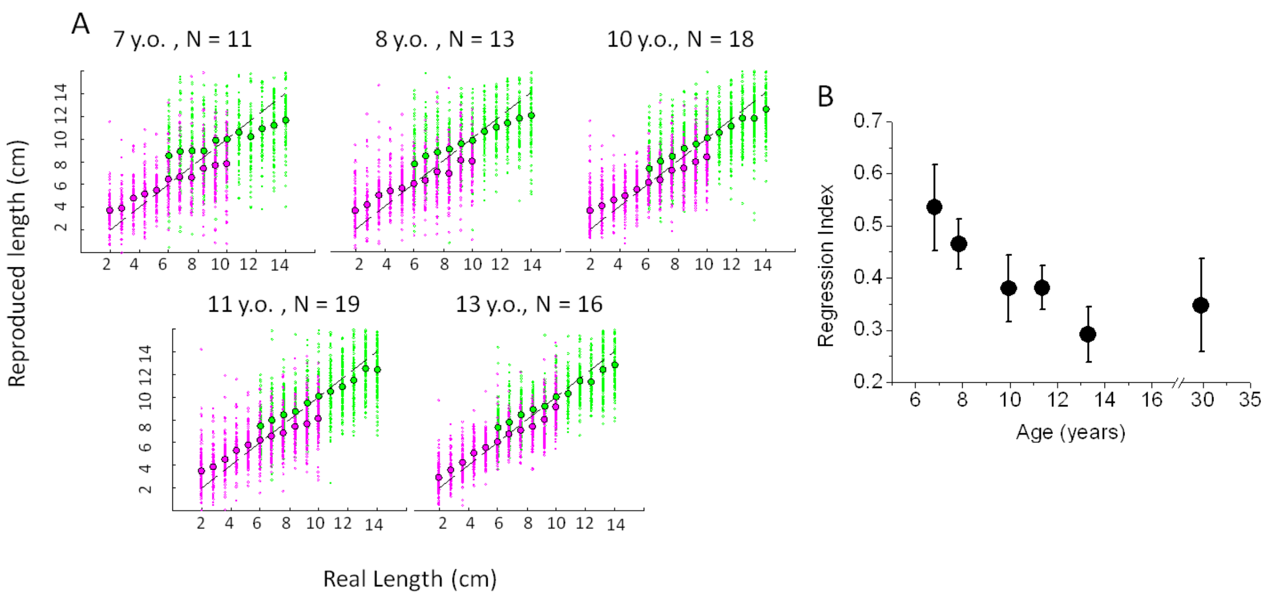

Fig. 3. A) Reproduced length as a function of stimulus length for the different age groups. Same color code as Fig. 2. B) Average regression index as a function of age. Error bars represent group standard errors

This trend follows the improvement in visual precision in size perception (see e.g. [2]), as the variability associated to perceptual estimates of size decreases progressively during childhood, at least until 10 years of age. Moreover, the tendency seems to indicate that during late childhood kids adopt even lower regression values than adults, as if giving more relevance to veridicality than adults

C. Accuracy wins over central tendency in interactive scenarios

In adults when space reproduction is inserted in an interactive framework, the central tendency almost disappears (see Fig. 4A). Indeed, subjects on average reproduce as accurately as possible (not considering an individual constant bias) the distance presented by the other agent. In fact, on average the regression index decreases significantly in the interactive condition with respect to the space reproduction task performed in solo (one-sided, two-sample t-test, $t(6.95)= 2.55324$, $p= 0.019$, see Fig. 4B).

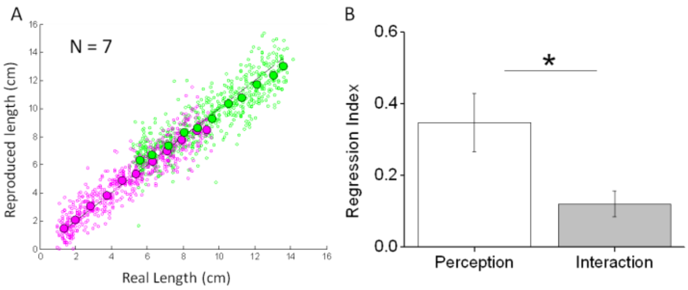

Fig. 4. A) Reproduced lengths as a function of stimulus length in the interactive task. Same color code as Fig. 2. B) Average regression index as a function of task type. Error bars represent standard errors. The star indicates significant difference in a t-test ($p < 0.05$.)

D. General results

Our results show that in adults the central tendency is present not only for time, but also for space perception. Younger children show a stronger regression to the stimulus mean. Adult-like regression level is attained only around 11-13 years of age, following the reduction in perceptual variance associated with development. A tendency for preferring accuracy over regression to the mean is observed at the later developmental stage, but it still needs to be investigated in more detail. Most interestingly, the central tendency is almost abandoned in interactive tasks, where the accuracy of the reproduction is maximized with almost no regression to the stimulus average.

IV. DISCUSSION

The central tendency mechanism is a fundamental principle of optimization adopted in human perception, not dissimilar to a filtering approach that takes into consideration a (moving) window of measures to obtain a better estimation of a certain quantity. An important question is under what circumstances its implementation could become advantageous also in robotics. Our study confirms that sacrificing accuracy for noise-robustness can be beneficial for perception of various quantities (e.g., time and space) when sensory precision is low, as during development. However, in interactive scenarios accuracy is preferred over noise-robustness, suggesting that the adoption of central tendency is task-dependent. These findings indicate that the implementation of the central tendency mechanism should not be ubiquitous, but would need to be considered as a function of the task and of the variance of the robot sensory inputs.

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