# SEMINARS IN ARTIFICIAL INTELLIGENCE

## HUMAN ROBOT SPATIAL INTERACTION


Marc Hanheide

UNIVERSITY OF LINCOLN

SAPIENZA UNIVERSITÀ DI ROMA

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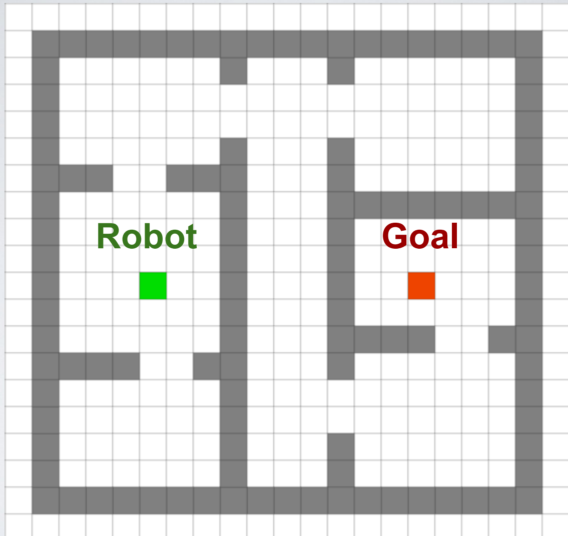
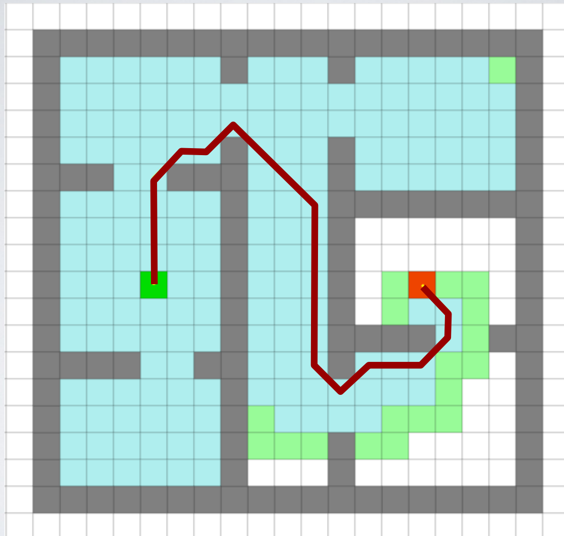
# ROBOTIC NAVIGATION







https://qiao.github.io/PathFinding.js/visual/

# HOW ABOUT HUMANS?

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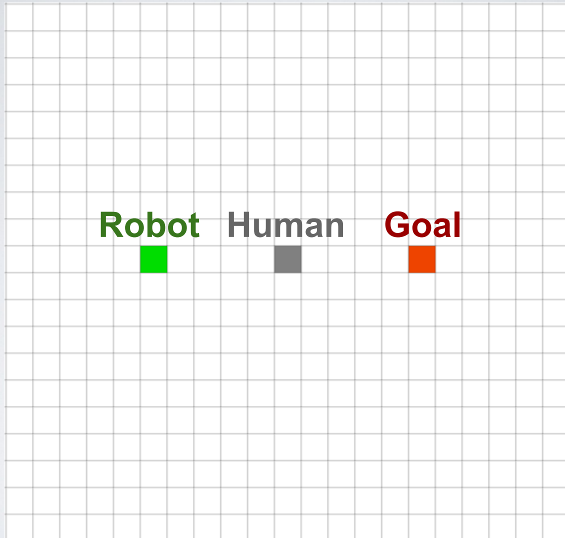


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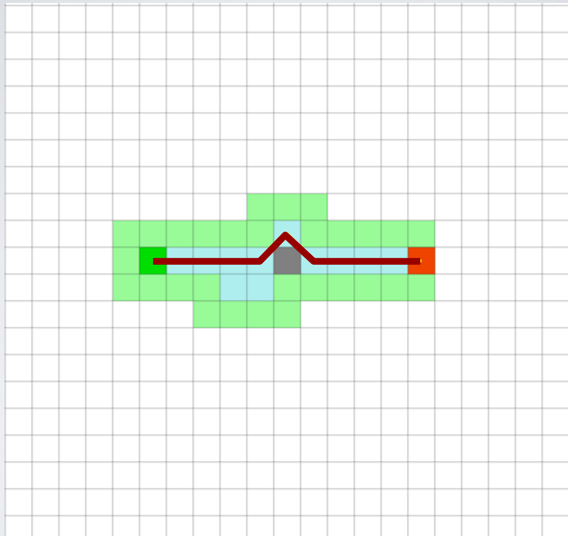

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# NON-VERBAL COMMUNICATION (BODILY COMMUNICATION)

Argyle, M., 1988. Bodily communication 2nd ed.,

Bodily communication, or non-verbal communication (NVC), plays a central part in human social behaviour. Recent research by social psychologists and others has shown that these signals play a more important part, and function in a more intricate manner, than had previously been realized. If we want to understand human social behaviour we shall have to disentangle this non-verbal system.

We know what these non-verbal signals are:

facial expression
gaze (and pupil dilation)
gestures, and other bodily movements
posture
bodily contact
spatial behaviour
clothes, and other aspects of appearance
non-verbal vocalizations
smell

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# NON-VERBAL COMMUNICATION (BODILY COMMUNICATION)

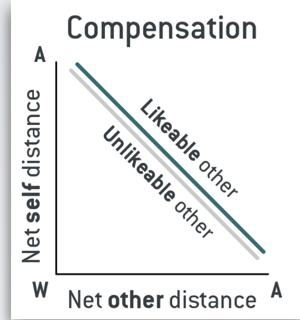
Argyle, M., 1988. Bodily communication 2nd ed.,

state of A → encodes NV signal → decodes state of B



# CLOSENESS

- **The Compensation Model**
- model of interpersonal distancing that suggested an *equilibrium* in the distance between two individuals
- when individuals increase their closeness (or decrease distance) with their partners, their partners *compensate* for this increase by decreasing closeness with them.
- more eye-contact => increase distance…

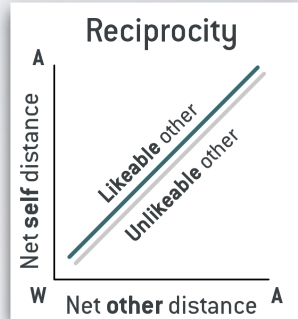



Mumm, J. & Mutlu, B., 2011. Human-robot proxemics. In Proceedings of the 6th international conference on Human-robot interaction - HRI '11. New York, New York, USA: ACM Press, p. 331.



# CLOSENESS

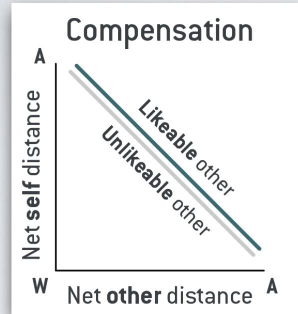
- **The Reciprocity Model**
- This second model suggests that, in dyadic interaction, when one increases closeness (or decreases distancing), the other reciprocates and increases closeness to the other person
- linear increase in participants' self-disclosure when the experimenter increased disclosure

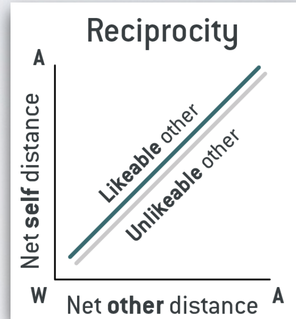



Mumm, J. & Mutlu, B., 2011. Human-robot proxemics. In Proceedings of the 6th international conference on Human-robot interaction - HRI '11. New York, New York, USA: ACM Press, p. 331.



# CLOSENESS

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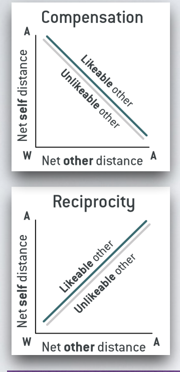
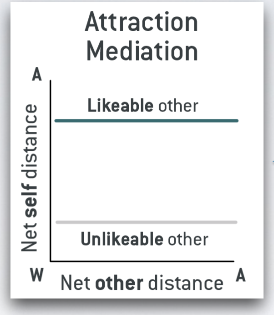


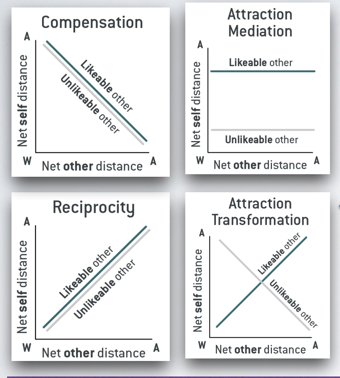

- attraction between the individuals at the onset of the interaction determines the distancing behavior.

Mumm, J. & Mutlu, B., 2011. Human-robot proxemics. In Proceedings of the 6th international conference on Human-robot interaction - HRI '11. New York, New York, USA: ACM Press, p. 331.





# CLOSENESS



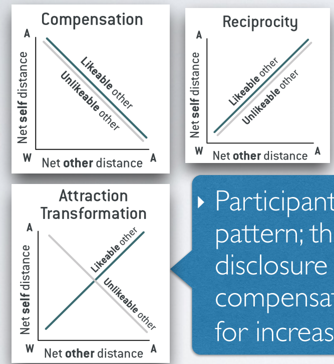

- incorporate the reciprocity and compensation models
- the level of attraction between individuals at the onset of the interaction affects whether individuals compensate or reciprocate.

Mumm, J. & Mutlu, B., 2011. Human-robot proxemics. In Proceedings of the 6th international conference on Human-robot interaction - HRI '11. New York, New York, USA: ACM Press, p. 331.





# CLOSENESS




facial expression
gaze (and pupil dilation)
gestures, and other bodily movements
posture
bodily contact
spatial behaviour
clothes, and other aspects of appearance
non-verbal vocalizations
smell

- Participants' nonverbal behaviour showed a different pattern; they reciprocated the liked confederate's disclosure by increasing the amount of gaze and compensated for the disliked confederate's attempt for increasing closeness by reducing it.

Mumm, J. & Mutlu, B., 2011. Human-robot proxemics. In Proceedings of the 6th international conference on Human-robot interaction - HRI '11. New York, New York, USA: ACM Press, p. 331.





# PROXEMICS


facial expression
gaze (and pupil dilation)
gestures, and other bodily movements
posture
bodily contact
spatial behaviour
clothes, and other aspects of appearance
non-verbal vocalizations
smell

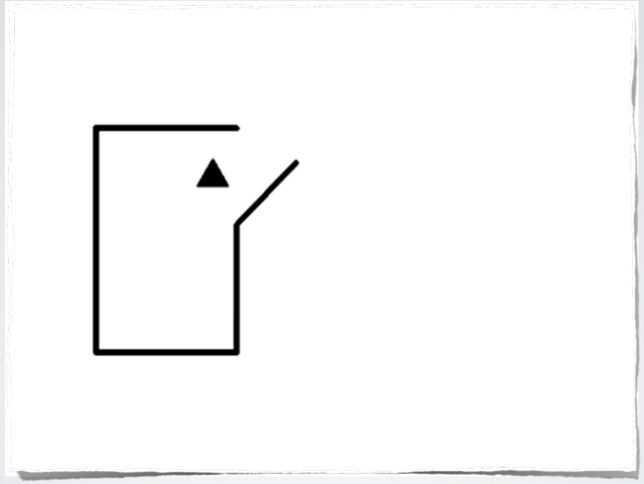
- Spatial behaviour is only among many non-verbal cues, but well studied in *proxemics*.
- and highly relevant for mobile robots

## "One cannot *not* communicate"

[Watzlawick, 1967]

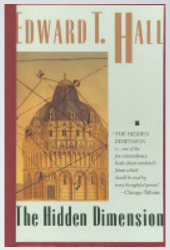



## THE COMMUNICATIVE POWER OF MOTION



Heider, Fritz and Simmel, Marianne (1944). An Experimental Study of Apparent Behavior. The American Journal of Psychology, 57(2), pp. 243-259






## PROXEMICS OR THE "HUMAN OBSTACLE"

Hall, Edward T. (1966). The Hidden Dimension. Anchor Books. ISBN 0-385-08476-5.

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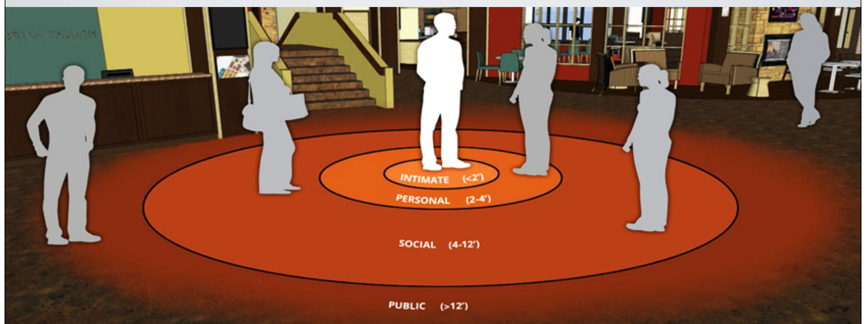

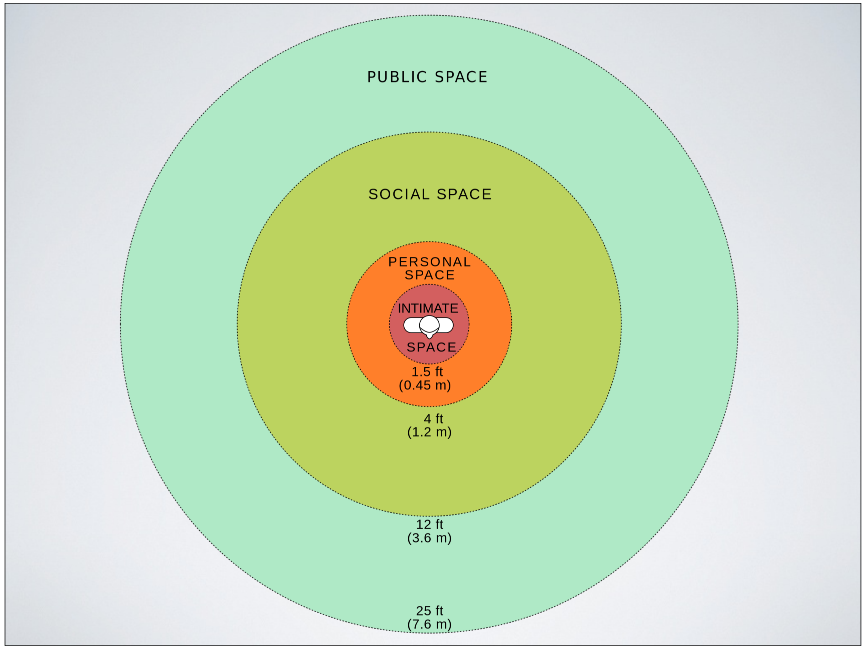


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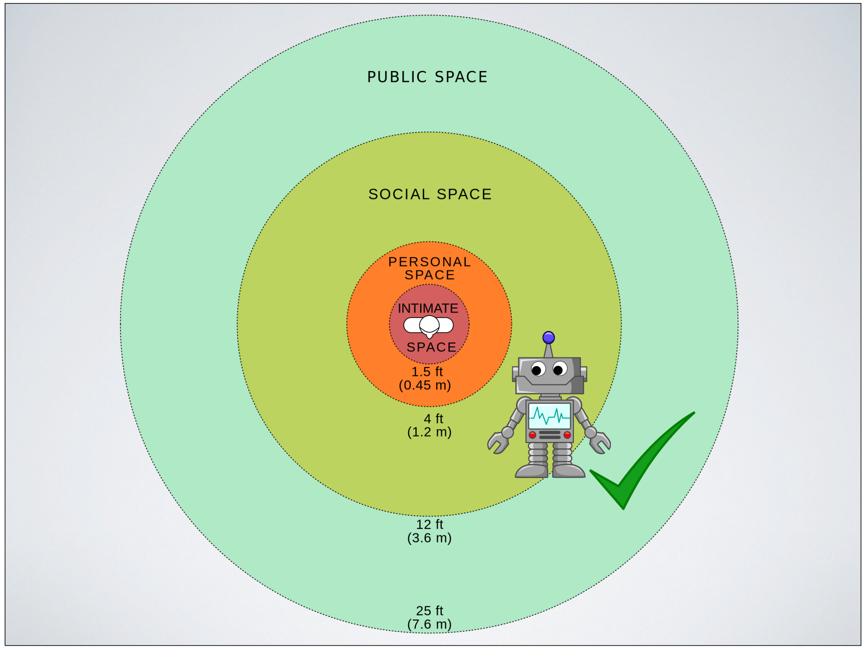


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# HRI PROXEMICS

Takayama, L. & Pantofaru, C., 2009. Influences on proxemic behaviors in human-robot interaction. In 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2009. pp. 5495–5502.

Walters, M.. et al., 2009. An Empirical Framework for Human-Robot Proxemics. In Procs of New Frontiers in Human-Robot Interaction: symposium at the AISB09 convention. pp. 144–149. Available at: https://uhra.herts.ac.uk/dspace/handle/2299/3794.

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# HRI PROXEMICS

- 1) Because experience with non-human agents might affect interactions with robots, we hypothesize that experience with **owning pets will decrease** the personal space that people maintain around robots.
- 2) Because familiarity between people decreases personal spaces between people and this seems to hold true in human-robot interaction, we hypothesize that **experience in robotics will decrease** the personal space that people maintain around robots.
- 3) Because people have more control over their personal space when they are the **ones approaching** (as opposed to being approached), we hypothesize that people will maintain **larger personal spaces** when being approached by a robot than when they are approaching the robot.
- 4) Because **mutual gaze** increases personal spaces between people, we hypothesize that when the robot's head is oriented toward the individual's face, the individual will **require a larger separation** than when the robot's head faces the person's legs.

Takayama, L. & Pantofaru, C., 2009. Influences on proxemic behaviors in human-robot interaction. In 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2009. pp. 5495–5502.

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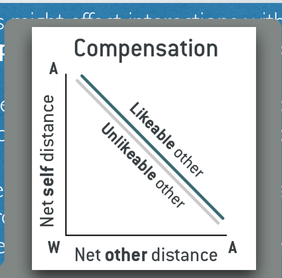


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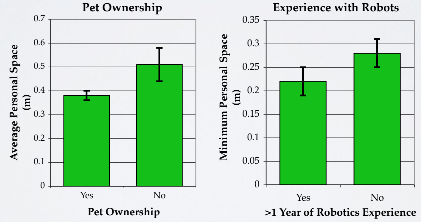



Fig. 3. Personal experience influences on proxemic behaviors with robots. The left-hand chart shows that participants who had owned a pet at some point in their lives were comfortable at closer average distances to the robot than those who had never owned a pet. The right-hand chart shows that robotics experience also correlates with smaller comfortable distances.



# HRI PROXEMICS

- ~~3) Because people have more control over their personal space when they are the **ones approaching** (as opposed to being approached), we hypothesize that people will maintain **larger personal spaces** when being approached by a robot than when they are approaching the robot.~~

TABLE I

Repeated Measures Analysis of Covariance: Effects of Pet Ownership, Experience with Robots, and Robot vs. Person Approach Upon Minimum Distance Between Person and Robot

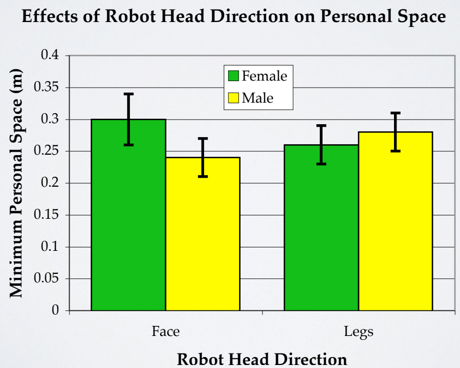
| | Sources of Variance for Minimum Proxemic Distance | Sum of Squares | df* | Mean Square | F |
|---|---|---|---|---|---|
| within | Robot vs. person approaches | 0.002 | 1 | 0.002 | 0.30 |
| within | Robot vs. person approaches x Pet ownership | 0.000 | 1 | 0.000 | 0.00 |
| within | Robot vs. person approaches x Robot experience | 0.001 | 1 | 0.001 | 0.13 |
| within | Error | 0.202 | 27 | 0.007 | |
| between | Pet ownership | 0.035 | 1 | 0.035 | 1.72 |
| between | Robot experience | 0.119 | 1 | 0.119 | 5.60** |
| between | Error | 0.621 | 27 | 0.022 | |

* *df* = Degrees of Freedom
** $p<.05$

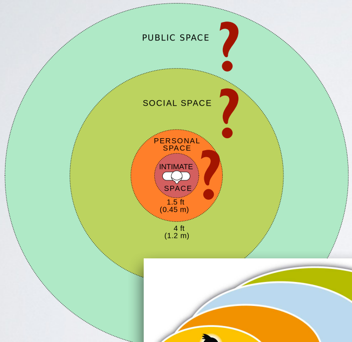


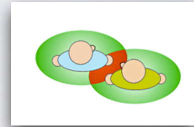
# HRI PROXEMICS

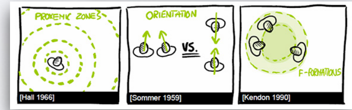
- 4) Because **mutual gaze** increases personal spaces between people, we hypothesize that when the robot's head is oriented toward the individual's face, the individual will **require a larger separation** than when the robot's head faces the person's legs.

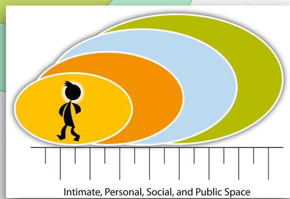


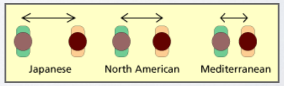
# PROXEMICS SPACES DEPEND ON MANY VARIABLES





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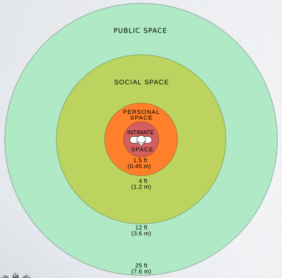



| Range | Situation | Personal Space Zone |
|---|---|---|
| 0 to 0.15m | Lover or close friend touching | Intimate Zone |
| 0.15m to 0.45m | Lover or close friend only | Close Intimate Zone |
| 0.45m to 1.2m | Conversation between friends | Personal Zone |
| 1.2m to 3.6m | Conversation to non-friends | Social Zone |
| 3.6m + | Public speech making | Public Zone |



# HRI PROXEMICS

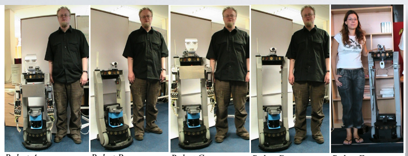
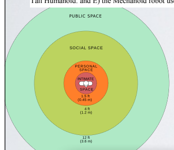



**Figure 1** The PeopleBot™ Robots used for the large HRI Studies: A) Short Mechanoid, B) Short Humanoid, C) Tall Mechanoid, D) Tall Humanoid. and E) the Mechanoid robot used for the robot voice style trial.

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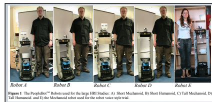
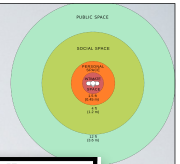
| Approach Context | Mean (cm) | Standard Error (mm) | 95% Confidence Interval (cm) | |
|---|---|---|---|---|
| | | | *Lower Bound* | *Upper Bound* |
| *Grand Mean* | 57 | 18.312 | 53.04 | 60.50 |
| *Interaction: Pass*<br>*Verbal*<br>*Physical* | 60<br>60<br>49 | 13.055<br>13.055<br>13.055 | 57.60<br>58.00<br>46.28 | 62.73<br>63.09<br>51.4.1 |
| *Appearance:*<br>*Mechanoid*<br>*Humanoid* | <br>51<br>62 | <br>10.830<br>10.486 | <br>48.71<br>60.11 | <br>52.98<br>64.24 |
| *Control: Robot*<br>*Human* | 57<br>56 | 18.870<br>21.069 | 53.39<br>52.02 | 61.07<br>60.60 |
| *Direction: Front*<br>*Side* | 58<br>55 | 20.510<br>18.433 | 54.12<br>51.44 | 62.47<br>59.04 |
| *Preferences:*<br>*Mechanoid*<br>*Humanoid*<br>*Short*<br>*Tall* | <br>60<br>56<br>61<br>55 | <br>17.393<br>17.946<br>18.349<br>16.967 | <br>46.80<br>61.57<br>53.56<br>54.81 | <br>54.22<br>69.22<br>61.3.8<br>62.0.5 |
| *Initial Uncertainty* | 71 | 67.770 | 57.04 | 84.27 |



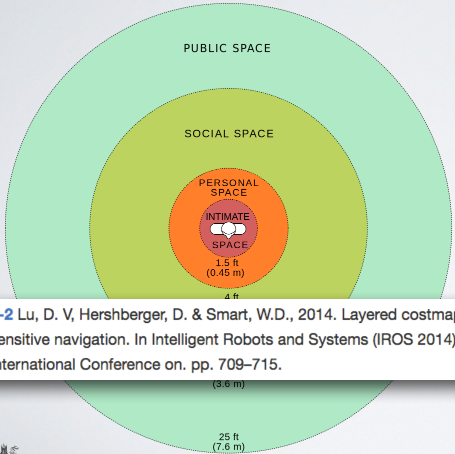


# HRI PROXEMICS




| Factor | Situation(s) | Context(s) | Base Distance = 57cm<br>Estimated Adjustment for Factor (± 0.5cm) |
|---|---|---|---|
| **Attribute or Factor of Robot** | | | |
| Mechanoid Robot | RH Approach<br>HR Approach | All | -3<br>-7 |
| Humanoid Robot | RH Approach<br>HR Approach | All | +3<br>-1 |
| Verbal Communication | RH Approach | Verbal Interaction | +3 |
| Giving object | RH Approach | Physical Interaction | -7 |
| Taking object | RH Approach | Physical Interaction | -7? |
| Passing | RH Approach | No Interaction | +4 |
| Direction from: | RH Approach | Front<br>Right/Left | +2<br>-2 |
| **Attribute or Factor of Human** | | | |
| Preferred Robot Humanoid | RH Approach | All Private | -3 |
| Preferred Robot Mechanoid | RH Approach | All | +3 |
| Preferred Height Tall | RH Approach | All | -1 |
| Preferred Height Short | RH Approach | All | +2 |
| Uncertainty or perceived Inconsistency | HR Approach | Initial Encounter | +13 |
| Verbal Communication | HR Approach | Verbal Interaction | +3 |
| Giving object | HR Approach | Physical Interaction | -7? |
| Taking object | HR Approach | Physical Interaction | -7? |
| Passing | HR Approach | No Interaction | +4 |

# 1ST PAPER: COSTMAPS




| | | |
|---|---|---|
| 3-2 Lu, D. V, Hershberger, D. & Smart, W.D., 2014. Layered costmaps for context-sensitive navigation. In Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on. pp. 709–715. | riccardo rinaldi | Daniele Evangelista |

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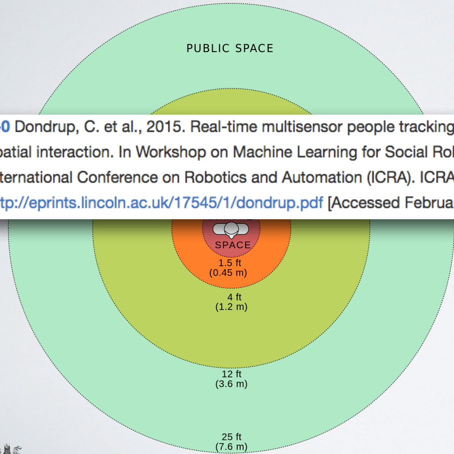
# 2ND PAPER: TRACKING




| | | |
|---|---|---|
| 3-0 Dondrup, C. et al., 2015. Real-time multisensor people tracking for human-robot spatial interaction. In Workshop on Machine Learning for Social Robotics at International Conference on Robotics and Automation (ICRA). ICRA / IEEE. Available at: http://eprints.lincoln.ac.uk/17545/1/dondrup.pdf [Accessed February 1, 2016]. | Ali Youssef | ? |

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# SOME QUALITATIVE PERSPECTIVES ON HRSI

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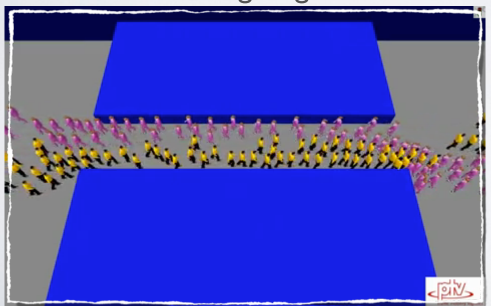
# IN THIS TALK: NARROW SPACES

Coordination or negotiation in Human-Robot close encounters

Mutual Understanding of goals and intention



http://www.youtube.com/watch?v=QkVOjbRq-I8

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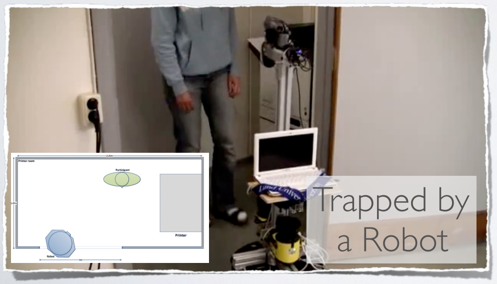
Head-on/Overtake Encounters in Corridors

**3 Studies**

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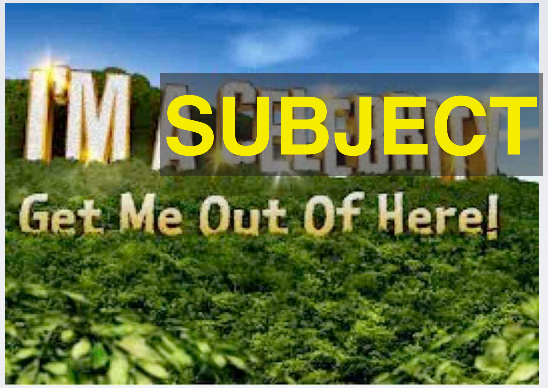
## Get me out of here - Motionings in HRSI -

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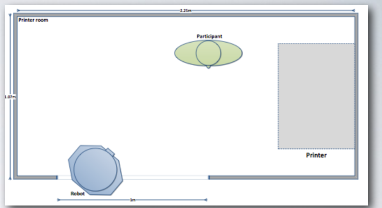
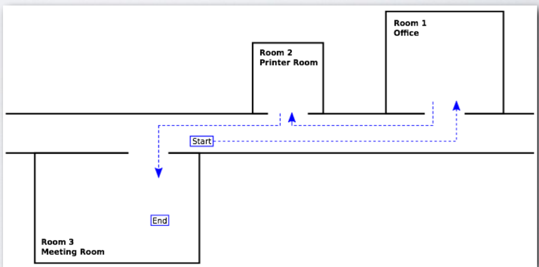
**How do humans (implicitly) signal to the robot when they want to leave?**




- 28 participants (36% female, 64% male, age: M = 29, SD = 8.21)
- embedded into a longer tour as cover story
- observational study

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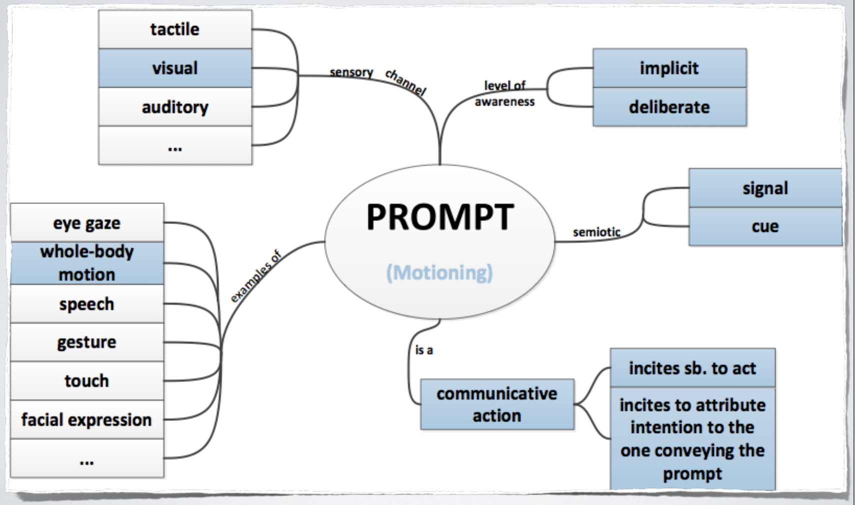
# OF PROMPTS AND MOTIONINGS




inspired by [A Green, 2009], taken from [A Peters, 2012]

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# MOTIONING - AN ATTEMPT FOR A DEFINITION

'To motion somebody' is an hyponym of 'to prompt somebody'. To motion somebody is an act of communication via motion with the entire body to incite someone to a communicative or spatial action.

[A Peters (2012): Spatial Coordination - Human and Robotic Communicative Whole-Body Motions in Narrow Passages, PhD Thesis]

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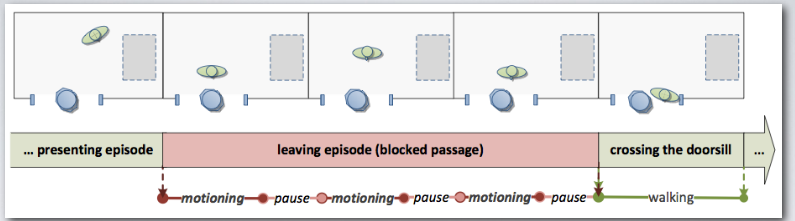


- Motionings are segmented according to pauses
- Only the "leaving" episodes is analysed
- The robot is remote controlled (WOZ) to eventually give way

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**Looking at the movements of legs and whole body**

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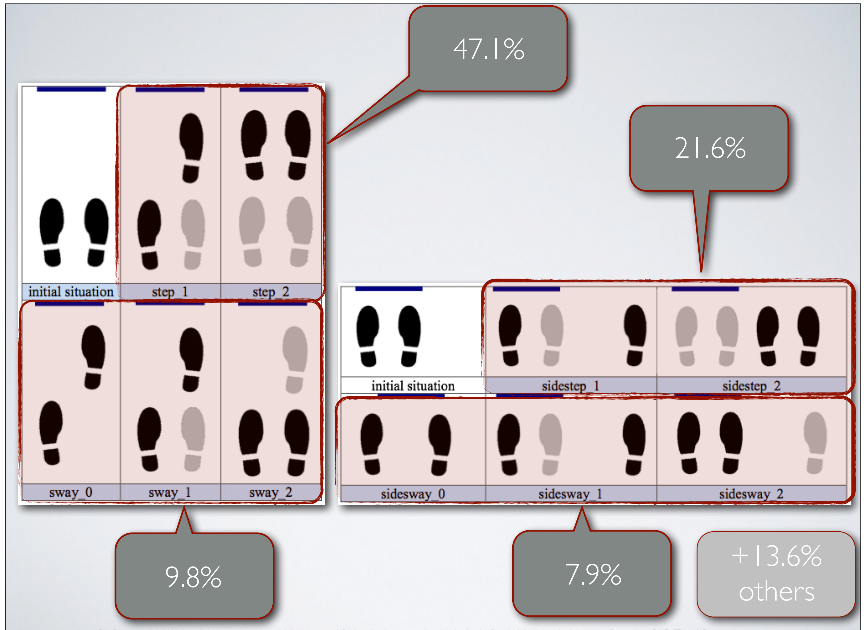


[A Peters (2012): Spatial Coordination - Human and Robotic Communicative Whole-Body Motions in Narrow Passages, PhD Thesis]

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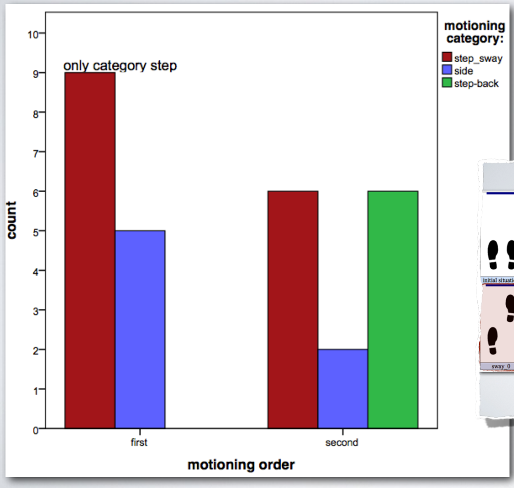
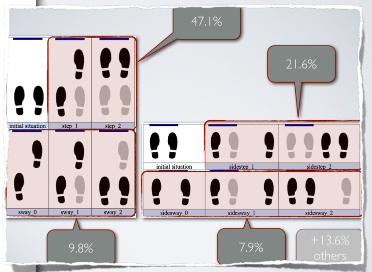
# ORDER MATTERS

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# SOME LESSONS LEARNED

- Motionings occur unsolicited and can be indicative
- They are highly situation dependent and difficult to detect reliably
- A (ordered) sequence of motionings can be more indicative
- Distance and timing is what matters

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# Representing HRSI Situations and Behaviour

How to effectively capture and reason about joint movement of human and robot?

Statistical models for time series

Order matters, different relative movements need to be represented

A Qualitative Trajectory Calculus

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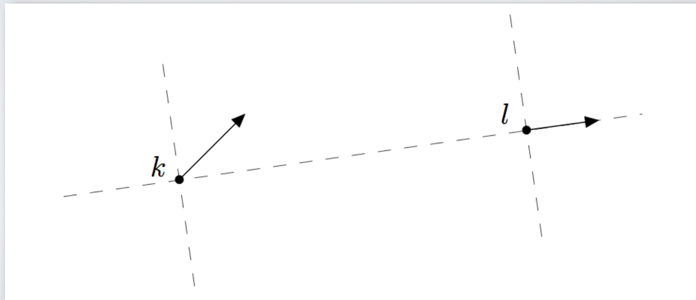
# QTC

- Represents the relative, qualitative movement of 2 points
- Different variants exist, but always represent states as tuples of '-','0', and '+'




[Van de Weghe, N. 2004. Representing and Reasoning about Moving Objects: A Qualitative Approach. Ph.D. Dissertation]

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# QTCc

$q_1$) movement of $k$ with respect to $l$

- $-$ : $k$ is moving towards $l$
- $0$ : $k$ is stable with respect to $l$
- $+$ : $k$ is moving away from $l$

$q_2$) movement of $l$ with respect to $k$

as above, swapping $k$ and $l$

$q_3$) relative speed of $k$ with respect to $l$

- $-$ : $k$ is slower than $l$
- $0$ : $k$ has the same speed of $l$
- $+$ : $k$ is faster than $l$

$q_4$) movement of $k$ with respect to $\overline{k\,l}$

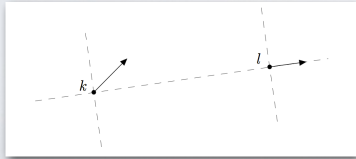
- $-$ : $k$ is moving to the left side of $\overline{k\,l}$
- $0$ : $k$ is moving along $\overline{k\,l}$
- $+$ : $k$ is moving to the right side of $\overline{k\,l}$

$q_5$) movement of $l$ with respect to $\overline{l\,k}$

as above, swapping $k$ and $l$

$q_6$) minimum absolute angle of $k$, $\alpha_k$, with respect to $\overrightarrow{k\,l}$ at time $t$

- $-$ : $\alpha_k < \alpha_l$
- $0$ : $\alpha_k = \alpha_l$
- $+$ : $\alpha_k > \alpha_l$




- for 2D space
- 6-tupel per state, e.g. (+,0,-,0,+,-)
- $3^6$=729 states!



# SIMPLIFIED QTCc

$q_1$) movement of $k$ with respect to $l$

- $-$ : $k$ is moving towards $l$
- $0$ : $k$ is stable with respect to $l$
- $+$ : $k$ is moving away from $l$

$q_2$) movement of $l$ with respect to $k$

as above, swapping $k$ and $l$

$q_4$) movement of $k$ with respect to $\overline{k\,l}$

- $-$ : $k$ is moving to the left side of $\overline{k\,l}$
- $0$ : $k$ is moving along $\overline{k\,l}$
- $+$ : $k$ is moving to the right side of $\overline{k\,l}$

$q_5$) movement of $l$ with respect to $\overline{l\,k}$

as above, swapping $k$ and $l$

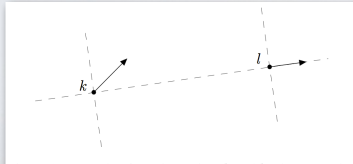


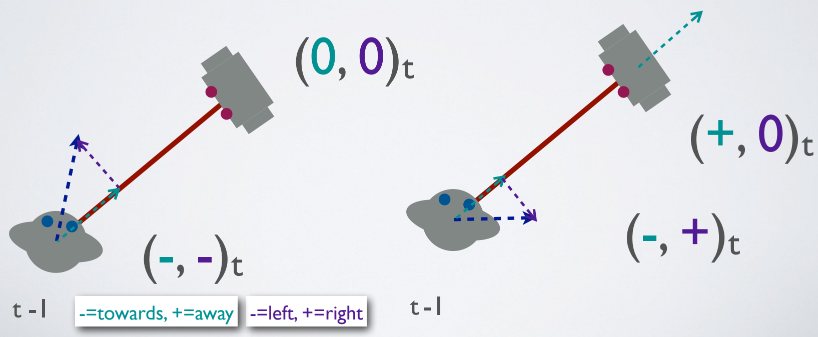

Figure 1: Example of moving points $k$ and $l$. The respective $QTC_C$ relation is $(-\,+\,-\,0)$.

- for 2D space
- 4-tupel per state, e.g. (-,+,-,0)
- $3^4$=81 possible states



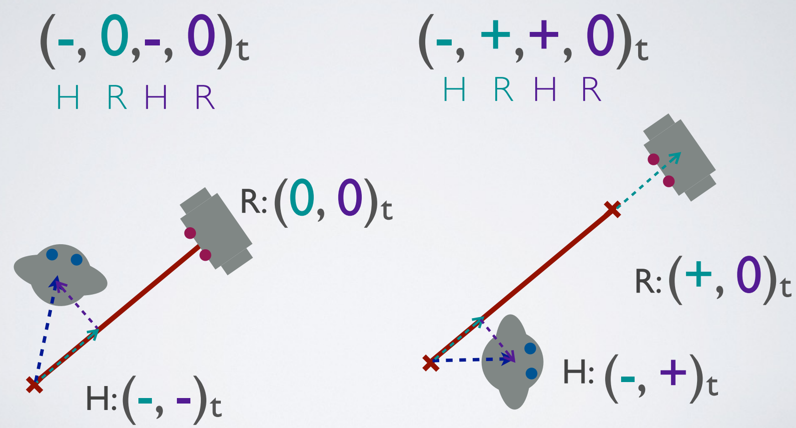
# QTCc - BY EXAMPLE

QTCc represents the relative motion of two points in a time interval with respect to the reference line that connects them on a 2D plane.






# QTCc - BY EXAMPLE

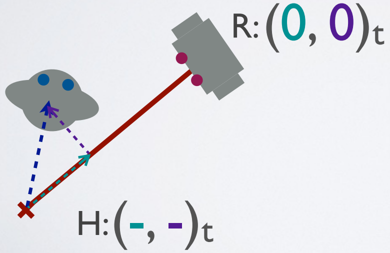


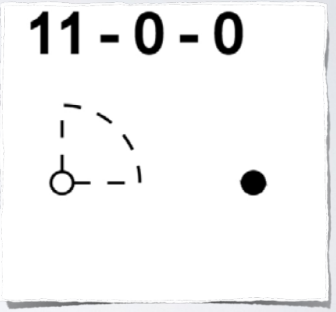
# QTCc STATE

$(-, 0, -, 0)_t$

H R H R

state no. H R H R



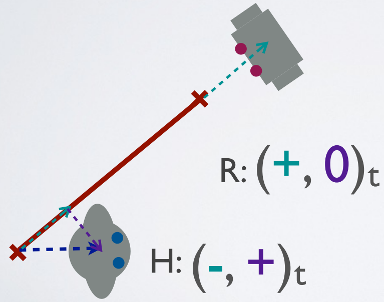


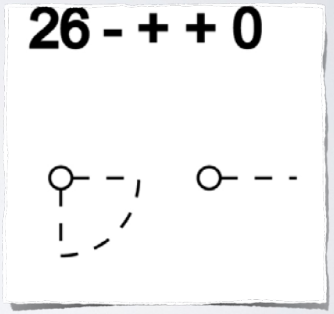

# QTCc STATE

$(-, +, +, 0)_t$

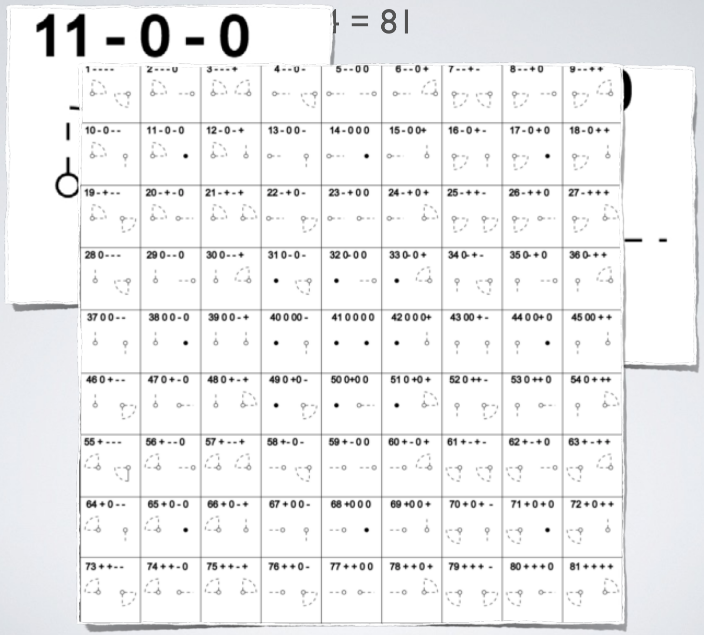
H R H R

state no. H R H R



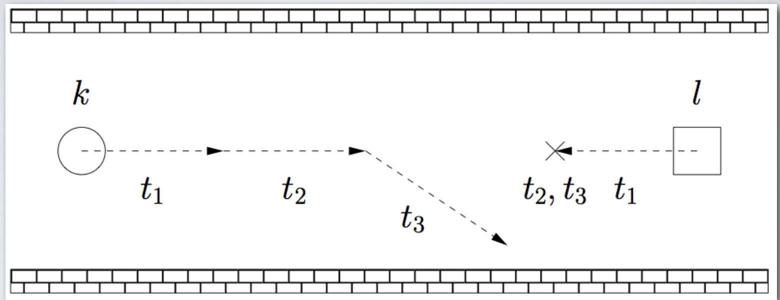








# QTCc SEQUENCES

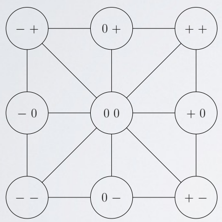



How to represent this sequence?

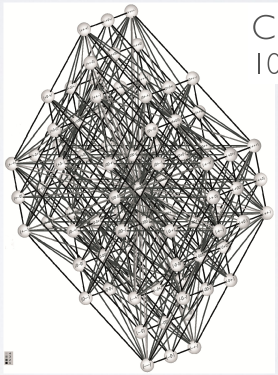
$$(- - 0\ 0)_{t_1} \rightsquigarrow (- 0\ 0\ 0)_{t_2} \rightsquigarrow (- 0 + 0)_{t_3}$$

# CONCEPTUAL NEIGHBOURHOOD DIAGRAMS

- Only certain transitions are valid in QTC




CND for $QTC_B$
16 out of 36

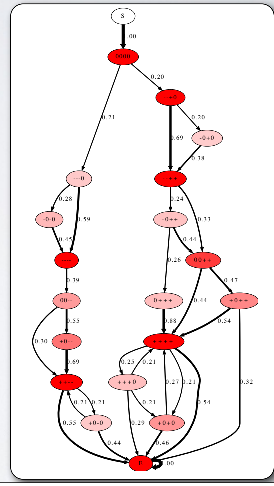


CND for $QTC_C$
1088 out of 3240



# REPRESENTING HRSI BEHAVIOUR AS QTC-MM

- Take the CND and create a (hidden) Markov Model topology from it
- Add start and stop states
- Discretise Motion of Human and Robot into QTC states
- Train with Baum-Welch Algorithm for set of specific behaviours



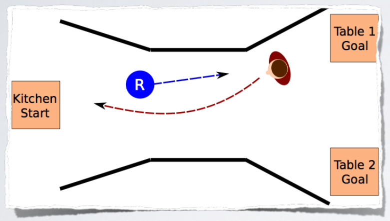


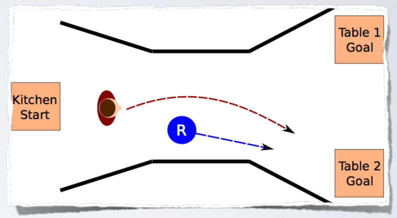
# RESTAURANT STUDY

- Motion Capturing
- Cover story: Serving in a Restaurant with a robot as a colleague
- Enforced narrow passage
- Aim: Identify motionings/signals that indicate hesitation to inform long-term adaptation
- Slowing down behaviour suggested by Lichtenthäler et al (see next!) vs baseline navigation



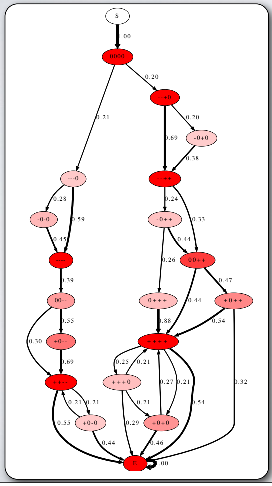

# RESTAURANT STUDY




- But here: discriminate different situations automatically using QTC-MM:
  - head-on
  - overtake

# USING QTC-MM TO RECOGNISE BEHAVIOUR



| Filter | | Classification rate | |
|---|---|---|---|
| Acc. | Time | Head-on | Overtaking |
| $1cm$ | $0.1s$ | $\mu = .9899 \pm .0076$ $\sigma = .0269$ | $\mu = .9669 \pm .0121$ $\sigma = .0427$ |
| $1cm$ | $0.3s$ | $\mu = .9659 \pm .0113$ $\sigma = .0399$ | $\mu = .8976 \pm .0152$ $\sigma = .0534$ |
| $5cm$ | $0.1s$ | $\mu = .9142 \pm .0153$ $\sigma = .0537$ | $\mu = .9171 \pm .0179$ $\sigma = .0629$ |
| $5cm$ | $0.3s$ | $\mu = .9502 \pm .0135$ $\sigma = .0475$ | $\mu = .8665 \pm .0251$ $\sigma = .0885$ |
| $10cm$ | $0.1s$ | $\mu = .8710 \pm .0185$ $\sigma = .0650$ | $\mu = .8502 \pm .0194$ $\sigma = .0683$ |
| $10cm$ | $0.3s$ | $\mu = .8879 \pm .0203$ $\sigma = .0715$ | $\mu = .8263 \pm .0267$ $\sigma = .0938$ |

5-fold cross validation recognition suggests that QTC-MM captures the differences in behaviours well

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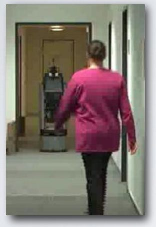
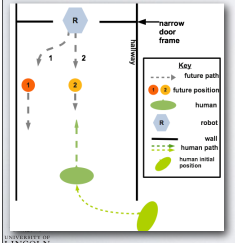
# Understanding Intention and Goals






Can we see changes in the humans' behaviour?

- Observational study with uninformed subjects (surprise encounter)
- Two different robot behaviours: defensive (1) and offensive (2)
- QTC-MM encoded

[Hanheide et al 2012, RO-MAN]

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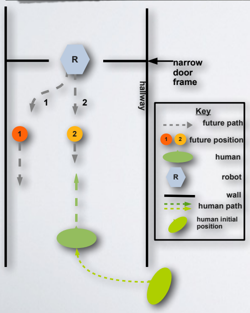
11 subjects in 2 conditions subject to QTC$_C$ analysis





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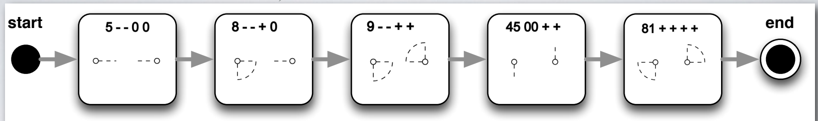
Human takes action to avoid first




Most Probably Sequence in condition 2

Questionnaire: Most frequent answers to the open question "What is the robot's intention"

1 "It avoids me"

2 "It wants to go down the corridor"

Peters 2012, "Hey robot, get out of my way - A survey on a spatial and situational movement concept in HRI" in Behaviour Monitoring and Interpretation

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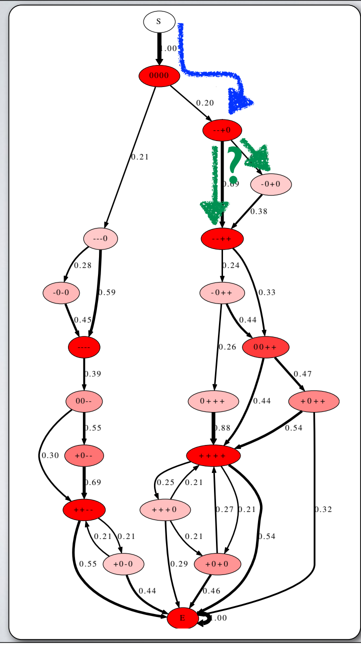
# (How) Can we make a robot react to perceived goals?

Idea: The robot can progress through the QTC state space by choosing appropriate *actions* that result in *intended* or *preferable* sequences.

Bellotto, N., Hanheide, M. & Weghe, N.Van De, 2013. Qualitative design and implementation of human-robot spatial interactions. Int Conf Social Robotics.





What should the robot do in response to human motion?

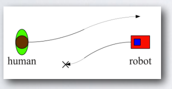
Partial Path indicates next best robot actions

cf. to MDP: actions are given by QTC transitions



Idea: The robot can progress through the QTC state space by choosing appropriate *actions* that result in *intended* or *preferable* sequences.

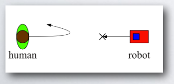
Approach and avoid (modelled combining $QTC_B$ and $QTC_C$):




(−000) ⇝ (−−00) ↗ (−−−0) ⇝ (−−−−) ↘ (00) ⇝ (++) ⇝ (+0)
↘ (−−+0) ⇝ (−−++) ↗

Robot takes action!

Approach and Withdraw




(−000) ⇝ (−−00) ⇝ (0−) ⇝ (+−) ⇝ (+0)



# CONCLUSION

**Summary**

- Motionings: whole body motion "prompt" to incite action
- QTC-MM as a generic model to capture HRSI
- QTC-MM to recognise behaviour and intentions

**Future work**

- QTC-MM reasoning
- Coping with noise in QTC discretisation
- Integration of Motionings signalling hesitation and "conflict" in a adaptation framework

# IN HINDSIGHT

- QTC-MM is a powerful representation and can be extended, but
  - it doesn't capture body orientation and micro movements
  - combinatorics!
- More context is needed to detect motionings
- Robot actions need to be modelled to account for their communicative effects







Annika Peters
Bielefeld

Christian Dondrop
Lincoln

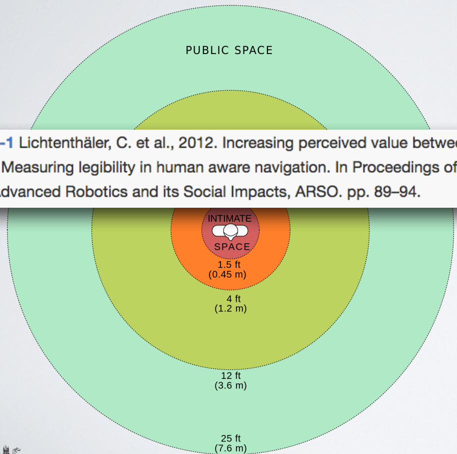
Elin Anna Topp
Lund

Nicola Bellotto
Lincoln

**Thank You!**



# 3RD PAPER: LEGIBILITY

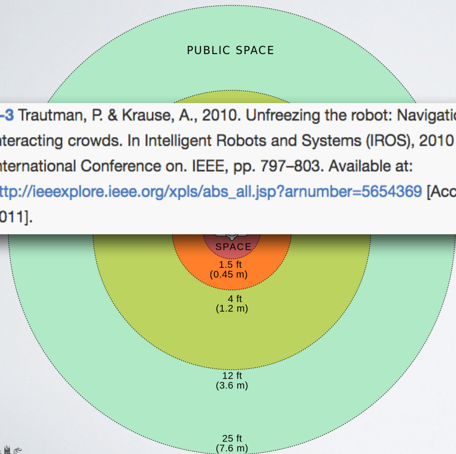



| | | |
|---|---|---|
| 3-1 Lichtenthäler, C. et al., 2012. Increasing perceived value between human and robots - Measuring legibility in human aware navigation. In Proceedings of IEEE Workshop on Advanced Robotics and its Social Impacts, ARSO. pp. 89–94. | Lorenzo Steccanella | Wilson Villa |

SAPIENZA UNIVERSITÀ DI ROMA

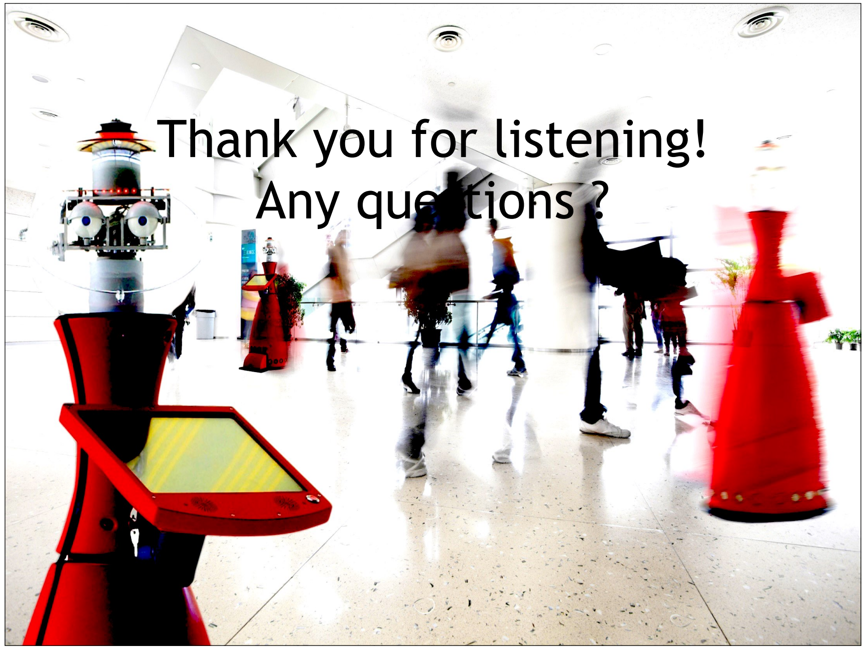


# 4TH PAPER: (UN)FREEZING THE ROBOT




| | | |
|---|---|---|
| 3-3 Trautman, P. & Krause, A., 2010. Unfreezing the robot: Navigation in dense, interacting crowds. In Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on. IEEE, pp. 797–803. Available at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5654369 [Accessed March 29, 2011]. | Francesco Sapio | Massimiliano Mancini |

SAPIENZA UNIVERSITÀ DI ROMA


Thank you for listening!
Any questions ?