long have we got?’ The answer was not immediately apparent
impending doom, the question on everyone’s lips was ‘How
on a collision course with the solar system. Faced with the
created a disaster scenario in which the eponymous cloud is


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Human Movement

Department of Motor Systems Laboratory, University of Queensland, St Lucia 4072, Australia.

tel: +61 7 3365 6240
fax: +61 7 3365 6877
e-mail: jameset@ hms.uq.edu.au

Review

Visually timed action: time-out for ‘tau’?

James R. Tresilian

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Tresilian – Visually timed action

moving objects – such as catching or hitting a ball – could be timed. The method is presented in Fig. 1 and shows that an object’s time-to-arrival or time-to-collision (TTC) can be obtained from the ratio of the object’s image size to the rate of change of size. Lee (Ref. 6) gave this ratio the special name tau (τ).

When hitting or catching a ball, your movements usually need to be timed very precisely so that you get to the right place at the right time to make the hit or catch. In games like baseball or cricket, the temporal precision required to hit a home run or a six is about ±2 ms (Ref. 4). Temporally co-ordinating your movements with external events to this level of precision requires accurate and reliable anticipatory timing information and it might be the case (Ref. 5) that it is visually available and does not involve prior measurement of speeds, distances or accelerations. Because τ requires no complex computations, it becomes a paradigm example of J.J. Gibson’s ecological approach (Ref. 7). This approach supposes that the information required for accurate perception of the world is entirely present in the stimulus: hypothesis testing, logical inference, the addition of information from memory or other constructive processes are unnecessary for understanding perceptions (Ref. 7; see Box 1). Gibson emphasised the identification of stimulus variables that specify perceived aspects of the world (‘constancy’). Tau has been used as a concrete example of such a variable and to illustrate how non-constructivist perception is possible.

The use of τ for timing interceptive actions is claimed to be supported by a body of empirical data. Lee provided evidence that τ is the basis for the timing of wing retraction in diving gannets (Ref. 7), as well as for ball-punching and keeping humans (Ref. 7). It has also been implicated in the timing of leg extension in landing house flies (Ref. 8) and hawks (Ref. 9) and in the timing of ball hitting and catching (Ref. 10). Psychophysical experiments have established that human observers are sensitive to τ (Ref. 11) and electrophysiological studies have found neurons sensitive to 1/τ in the optic tectum of pigeons (Ref. 12). These data have been interpreted as supporting a particularly simple account of how interceptions are made (Ref. 13). This account will be called the ‘τ-hypothesis’ and can be stated as follows:

The information provided by τ is used to make estimates of TTC which determine the timing of interceptive actions, avoidance manoeuvres and psychophysical judgments of TTC.

This hypothesis is a general account of interceptive timing skill. It applies to gannets (Ref. 7), flies (Ref. 8) and hawks (Ref. 9) as well as to people because the information upon which timing is based (τ) is present within the optic array – the visual stimulus medium described independently of any imaging system (e.g. eye). However, recent work has established that this τ-hypothesis is false (Ref. 14, 15), and the weight of data that has been marshalled in its support does not, on close examination, support it at all (Ref. 16). It is vitally important to note that the falsity of the τ-hypothesis does not entail rejecting the idea that τ is involved in TTC estimation – indeed, the empirical evidence suggests that τ is involved, at least in some tasks (Ref. 16), but is not the only source of information for TTC estimation.

Why the τ-hypothesis is false

Reasons for rejecting the τ-hypothesis derive from direct experimental testing and logical arguments based on empirical observations. To address the latter first: τ is limited as a source of TTC information by four factors: (1) it neglects accelerations; (2) it provides information about TTC with the eye; (3) it requires that an object be spherically symmetric; (4) it requires that the object’s image size and expansion rate be supra-threshold (Ref. 17). These factors seriously restrict the utility of τ as a source of TTC information (Ref. 17, 18, 19, 20). On its own, τ cannot account for how people time interceptions for short falls under gravity (Ref. 18, 21, 22). It is vitally important to note that the falsity of the τ-hypothesis does not entail rejecting the idea that τ is involved in TTC estimation – indeed, the empirical evidence suggests that τ is involved, at least in some tasks (Ref. 16), but is not the only source of information for TTC estimation.

Perhaps there are tasks in which τ could, in principle, provide sufficient timing information. However, the only studies that have shown that τ on its own can be used to make
Box 1. Perception and information

It is a logical fact that the visual stimulus (either retinal image or optic array) does not contain sufficient information to support veridical perception (Retin a). Rather, perception appears to require that information be added to that obtained from the stimulus. Gibson realized that what is logically true is not necessarily ecologically true (Ref. c). Although there is an indefinitely large number of logically possible environments that could give rise to a particular stimulus, many of these will not be ecologically possible — coming to the physical laws and regulation that constrain the structure and behaviour of the ecological world (Ref. d) — thus, they are irreducible for understanding perception. Gibson hypothesized that in normal (ecological) conditions the information available in the stimulus is sufficient for adequate perception of the environment (Ref. c).

Gibson’s rethinking of the informational basis for perception required a rethinking of what the perceptual processes are doing: if something is there (the information is present in the stimulus) then you do not have to construct or compute it. Perception, Gibson suggested, is more like the process by which radio receivers pick up radio transmissions: the information is ‘out there’ ready to be received — your radio receiver does not compute it. In order for this analogy to make sense there must be stimulus analogues of radio transmissions — sources of information in the stimulus to which the perceptual systems are tuned. Gibson referred to these as ‘invariants’. In general terms, invariants are considered to be complex, spatiotemporally distributed, ‘higher order’ structures (Refs c–e).

In effect, therefore, Gibson proposed three hypotheses:

(a) that the stimulus is insufficiently rich in ecological conditions;
(b) that information is carried by invariants, which specify environmental properties and states of affairs;
(c) that invariants are detected directly: they are not computed or constructed from simpler or lower-order stimulus variables.

Notes that it is possible for the stimulus to be informationally sufficient but for perceptual processing to be indirect and for invariants to be non-stationary. Indeed, the account of TTC perception described in the main text of this article assumes exactly this: it accepts (a) but rejects (b) and (c). A similar position has been adopted by Cutting (Ref. f), who accepts hypothesis (A), rejects (B) and presents a version of (B) rather different from that proposed by Gibson. Cutting’s version allows for multiple invariants specific to a perceivable aspect of the environment, whereas Gibson allowed only one. The position adopted here differs from that of both Gibson and Cutting by rejecting the salubrity of Gibson’s concept of invariants. Instead there are proposed to be individually ambiguous and partial sources of information, traditionally known as cues. A given cue might be sufficient for one task but not another. In the latter case, several cues combined together might provide the necessary information.

References


Box 2. Some alternatives to tau

An example of a binocular information source that can be used as an alternative to τ can be derived from the geometry shown in Fig. 1A, which represents the simplest case (Ref. 2b). The point M is moving with speed V directly towards the midpoint between the eyes; point F is fixed. Simple trigonometry establishes that,

\[ \tan \gamma = \frac{X}{V} \quad (1) \]

By definition (and incorporating (1)), we can write,

\[ \tan \gamma = \tan \left( \frac{X_1}{V_1} \right) = \frac{X_2}{V_2} \]

If point F is at effective optical infinity (more than 6 m distant), then its binocular parallax (α) is zero. Thus, for sufficiently distant points F, equation (2) becomes,

\[ \tan \gamma = \frac{X}{V} \quad (3) \]

Following differentiation with respect to time, and some rearrangement, equation (3) yields the relationship,

\[ \frac{d\gamma}{dt} = \frac{1}{2X} \quad (4) \]

where \( \alpha \) is the horizontal binocular disparity of M relative to a distant point F. For the rate of change of disparity and X/V is the time remaining before M reaches the mid-point between the eyes.

In Fig. 1B an object is shown moving with constant velocity V towards an interception point p. From this geometry a source of TTC information can be derived (Refs 2b,c), which informs about the moving object’s TTC with any post specularly identifiable point p. The sine rule establishes that,

\[ \frac{d\gamma}{dt} = \frac{V}{X} \quad (5) \]

Differentiating this with respect to time and noting that \( \beta \) is constant, yields, after some rearrangement,

\[ \frac{d\gamma}{dt} = \frac{V}{X} \quad (6) \]

Noting that \( X = -V \) and that \( -B/B' = \tau \), we can rewrite equation (6) as follows:

\[ \frac{d\gamma}{dt} = \frac{V}{X} = \frac{1}{\tau - \frac{V}{X}} \quad (7) \]

Where X/V is the time remaining before the moving object reaches point p, and the right-hand side contains only variables that can, in principle, be measured by the visual system. These sources of information (equations 4 and 7) are used accurately during quality testing of proposed or observed TTC judgments.

References

Box 3. Measurement and representation of tau

It has been proposed that measurement of $\tau$ from the retinal image involves the prior measurement of image size and tau of image expansion (Ref. a) with $\tau$ being derived in a subsequent processing stage. This could be done simply by dividing image size by expansion rate (Ref. a) or by using size-expansion rate opponent.

An opponent mechanism could compute the difference between size ($\Theta$) and expansion rate ($\hat{\Theta}$). If $\Theta \hat{\Theta} = 1$ then the difference, $\Theta - \hat{\Theta}$, is zero. A mechanism that responds to $\Theta - \hat{\Theta}$ will have a threshold of 1 unit and will respond when $\Theta > 1$. More generally, if $\Theta - \hat{\Theta}$ is threshold and a mechanism that responds when $\Theta > \Theta R$ has threshold is. Neurons that behave in this fashion have been discovered by Frost and colleagues in the accessory optic system of the pigeon brain (Ref b,c). These neurons start to fire when $\Theta R$ reaches a threshold value and continue to fire (at a constant rate) when this threshold is exceeded. The value of $\Theta R$ is thus directly related to the total number of threshold neurons that are active. A possible model of a detector based on these results and ideas is shown in Fig. 1.

Frost and colleagues’ finding that the neurons are sensitive to $\Theta$ rather than $\Theta R$ is significant. It is not obvious that the nervous system should represent TTC information in units of time. By definition, TTC is large when collision is a long way off but small when collision is imminent: a signal that carries TTC will be ‘small’ close to collision. This is the opposite of what is likely to be most useful; that is, a large ‘largest’ signal when collision is imminent and a small signal when it is distant.

An alternative is to use the reciprocal of TTC (e.g. $1/\Theta$), a quantity Koenderink has referred to as ‘nearness in time’ or ‘immediacy’ (Ref. a) as an impending collision gets nearer in time, the immediacy gets larger. However, accurate estimates of a perceptual variable require that small differences be discriminable. An information channel in which noise is proportional to signal magnitude will have a reduced ability to discriminate small differences when signals are large (this follows from Weber’s law). Thus, there is a dilemma in TTC measurement: a signal should be more salient as collision approaches (immediacy is better) but greater sensitivity is required as collision approaches (TTC is better). The detector in Fig. 1 could help resolve this dilemma from the retinal image involves making a button-press response which coincides in time with the object’s arrival at a designated location (prediction-timing tasks). Some of the perceptual variables that have been implicated in interceptive timing and relative TTC judgments are given in Table 1.

The finding that many different variables, sensory systems and sources of information can contribute to estimates of TTC is what might be expected of a biological system. Biological perception is the achievement of an adaptive, neural dynamic system, which is in a continuous state of adjusting itself to the informational demands of behaviour by exploiting regularities in the stimulus input\(^{30}\). Performance of any given class of timing tasks, such as timing tasks, is likely to involve a patchwork of approximate and opportunistic computations and cues\(^{33}\)—perceptual systems ‘never miss a good trick’\(^{35}\). Under this conception, the system will

![Fig. 1. Hypothetical model for computing immediacy (reciprocal of TTC). Immediacy is calculated from independent image size ($\Theta$) and expansion rate ($\hat{\Theta}$) channels based on known properties of neurons in the nucleus rotundus of the pigeon brain (Ref. b,c). The size and expansion channels feed into a population of threshold neurons whose outputs ($T_i$) depend upon their inputs ($\Theta, \hat{\Theta}$) according to the rule shown. The output of the summing unit is proportional to the number of threshold units that are firing at a given time ($T_i$).](image-url)
task is associated with a particular set of variables. However, the currently available data do not force us to accept this second, rather unparsimonious option; it is possible to identify principles and constraints that allow a more theoretically motivated account to be formulated. A recent approach to this problem of information integration50,51 or fusion52. The latter can be broken down into two aspects: first, the construction of more specific, ‘higher-order’ cues from relatively primitive perceptual variables – for example, the construction of \( t \) from image size and rate of expansion (Box 3), or calculation of fine-order TTC from \( t \), the optical gap and the rate of gap constriction (Box 2); second, the combination of multiple cues. The best understood example of our combination is that of depth perception: many visual depth (relative distance) cues can be identified, including image size, motion parallax, height in the visual field, occlusion, texture gradients, blur, linear perspective and binocular disparity50,51. A body of empirical work supports the idea that in some situations at least, these cues are simply averaged together to obtain an overall depth estimate53,54. Recent evidence suggests that similar processes are involved in TTC perception, notably for the combination of monocular and binocular cues10,15. The question of how the integration process is organized is a new and important question for research in TTC perception and existing theoretical ideas can be usefully applied to it16.

The problem of cue selection emerges most noticeably in the context of relative judgment tasks (Fig. 2). These tasks are not actually timing tasks – the observer does not necessarily...
need to determine the TTC of the target stimulus; he simply needs to determine whether or not it will arrive earlier than the comparison stimulus. An observer could use anything that enabled such a judgment to be made, or which he thought would enable such a judgment. This expectation has been repeatedly confirmed. For example, in a study reported by Law and colleagues, observers were asked to judge which of two moving objects would reach a particular location first (see Fig. 2 A,B,C). In the absence of performance feedback, observers frequently applied a ‘closer-first’ rule to make their decision: the target closest in space to the designated location at the time of display termination was judged to be closer in time. Provision of performance feedback was found to reduce the prevalence of the closer-first rule, as it was used in a reliable prediction of which target arrived first. Therefore, it appears that one role for learning in these tasks is to deselect those sources of information that interfere with satisfactory performance.

The task-dependency of information usage is likely to be best understood from an analysis of the temporal accuracy requirements of different tasks. For interceptive actions it is often possible to define a time-window during which successful interception is possible and which can therefore quantify the timing requirements imposed on performance. Definition of such a window requires a rather precise description of how the interceptive task is executed. This is relatively straightforward for laboratory-based tasks whose execution can be controlled by appropriate design of apparatus (Fig. 3) and is possible to calculate for some of the more constrained sporting tasks such as batting in cricket and baseball. It is much more difficult to define in unconstrained real-world tasks such as catching. Catching can be performed in a variety of different ways and the time-window can vary quite considerably. For example, when catching a ball it is temporally much more demanding to reach out perpendicularly to the ball’s path and snatch it out of its trajectory than it is to move your hand in the plane of the ball’s path allowing the ball to fall into it.

So far little empirical effort has been directed at establishing the time-windows for real-world interceptive actions. Nevertheless, it is possible to provide a coarse taxonomy of such tasks and to use existing data to develop hypotheses about the type of information used.

First, actions that involve the actual interception of a moving target, and which define a precise time-window for successful performance (Fig. 3), should be distinguished from those tasks (such as avoidance and braking tasks) that do not define a precise time-window (they define a late temporal boundary but not an early one; the latter may be defined by the observer according to internally imposed criteria which presumably vary). The initiation of braking to a stop is an example of the latter type of task: theoretically, braking could be initiated at a particular TTC with the stopping location, but a recent study found that it was actually initiated at a particular distance. If the task does not impose the requirement of precise timing the available data indicate that TTC is either not used, or if it is used, it is in conjunction with other information.

Second, it is possible to identify a class of interceptive actions with time-windows that range from about ±2 ms to ±25 ms – these include one-handed catching, playing a tennis or table-tennis stroke, hitting the ball in cricket or baseball, and various laboratory tasks. These interceptive actions are executed rapidly with movement times of less than 500 ms, sometimes as little as 100–200 ms (Refs 11,12,60), and the time for which the object is seen prior to movement initiation is often only a few hundred milliseconds. Successful timing of these fast interceptive actions requires that accurate and reliable TTC information be obtained within a relatively short period of time.

Within the class of fast interceptive actions two subclasses should be distinguished: those that involve short falls under gravitational acceleration and those that do not. It is impossible to time precisely the interception of an object that falls a short distance (<3 m) from rest without taking acceleration into account. Assuming that acceleration is not measured from the retina, such interceptions must involve the use of acceleration information obtained from elsewhere. Because the acceleration due to gravity is a terrestrial constant, it is possible to determine its value and use it to obtain an estimate of TTC from a perceptual estimate of drop height: they are related by the equation $H = \frac{1}{2}gTTC^2$, where air-resistance is neglected. Table 2 presents a rough taxonomy of timing tasks and the types of information that they are likely to involve, based upon currently available knowledge.

Using information to control a response

Not only do different tasks involve different sources of information but the way in which the information is used in the control of the response is likely to differ between tasks and to change with experience and practice. A body of evidence – behavioural, neuroanatomical and neurophysiological – supports the idea that there are at least two functional streams of visual information processing within primates (including human) neocortex. These streams appear to support different functions: the dorsal stream is involved with visual processing for the control of skilled motor action (motor stream); the ventral stream is involved with processing that supports conscious visual perception and cognitive judgments (cognitive stream). The operation of the motor stream precedes largely automatically and without awareness. Although it is not yet completely clear whether the functional distinction between motor control and perceptual judgment corresponds with the anatomically defined streams.
it is clear that visuo-motor control can proceed without aware-
ness7,13, which is probably the normal state of affairs for fast
interceptive actions55. Thus, even if it turns out that con-
scious visual perception and cognitive visual operations are
supported by the same stream of information processing as
skilled visuo-motor control, it is likely that the latter taps this
stream as an early, pre-cognitive stage or level66. In other case,
skilled execution of interceptive actions appears to bypass
cognitive operations57, whereas laboratory-based tasks may
involve cognitive operations57,38. Thus, even if it turns out that con-
scious visual perception and cognitive visual operations are
process in these tasks is highly variable, with systematic biases
uncharacteristic of other
timing tasks, and cognitive modelling processes56–57 and men-
tal imagery57 have been implicated in their execution. Thus,
control of response is likely to be mediated by different
processes in laboratory tasks and interceptive actions59. As I
have argued in detail elsewhere14,38, it is not possible to make
generalizations about the information used to estimate TTC,
or about how this information guides behaviour, from results
obtained in any particular task.

Even within the class of skilled, fast interceptive actions
a number of possibilities exist for using TTC information
for controlling movement timing59. An early proposal was that
TTC information is used to trigger an action of constant
duration3,66. Thus, control of timing would simply reduce
TTC to initiating the movement at the correct moment: when
TTC reaches a particular value determined by the movement
duration (constant) and sensorimotor delays (also constant),
an initiation command is issued. It is now known that this
strategy is not generally used, movement duration typically
being quite variable, even in stereotyped actions of very short
duration such as table-tennis smashes70 and grasping move-
ments in catching12. Thus, it now appears that the nervous
system detect and how are they detected? Some suggestions have
been proposed and there are empirical data to support some of these, but a
clear and complete picture has yet to appear. How, for example, is an
interception timed when there is no direct perceptual information about
the location of the interception point?

• How do factors intrinsic to the central nervous system (thresholds,
  attention, time delays) and the musculo-skeletal system (muscle and limb
dynamics) affect the use of perceptual information in timing control?

• How do factors intrinsic to the central nervous system (thresholds,
  attention, time delays) and the musculo-skeletal system (muscle and limb
dynamics) affect the use of perceptual information in timing control?

• How is TTC information used to control movement? Are there tasks that
  involve a triggering mode of control? What other modes of control are
  used?

Conclusions
This article has reviewed recent work that shows conclusively
that the hypothesis which proposes the variable \( t \) as the
informational basis for TTC estimation is false. Instead, it is
clear that \( t \) is a component of a more complex picture and
it may or may not contribute to performance in a particular

**Outstanding questions**

• How do the requirements for temporal accuracy vary between tasks and
  what perceptual quantities are available to provide the timing
  information necessary to explain observed levels of performance? How
  do these requirements constrain the selection and integration of TTC
  related information? What other factors affect selection and
  integration?

• Exactly what sources of TTC information in addition to \( t \) can the nervous
  system detect and how are they detected? Some suggestions have
  been proposed and there are empirical data to support some of these, but a
  clear and complete picture has yet to appear. How, for example, is an
  interception timed when there is no direct perceptual information about
  the location of the interception point?

• How do factors intrinsic to the central nervous system (thresholds,
  attention, time delays) and the musculo-skeletal system (muscle and limb
dynamics) affect the use of perceptual information in timing control?

• How does the nervous system learn to eliminate irrelevant or
  compromising sources of information and how is the transition to a
  rapid, automatic processing mode achieved?

• How is TTC information used to control movement? Are there tasks that
  involve a triggering mode of control? What other modes of control are
  used?

**Table 2. Time-to-collision estimation: tasks and variables**

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<tr>
<td>Hit/catch an object</td>
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<td>Moving slowly</td>
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<td>20–100+</td>
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<td>Avoid object on</td>
<td>✓ (?)</td>
<td>to 3000+</td>
<td>✓</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?</td>
</tr>
<tr>
<td>collision course</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brake to a stop</td>
<td>✓ (?)</td>
<td>–</td>
<td>✓</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?</td>
</tr>
<tr>
<td>Prediction-motion tasks</td>
<td>✓ (?)</td>
<td>–</td>
<td>✓</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?</td>
</tr>
<tr>
<td>Relative judgment tasks</td>
<td>✓ (?)</td>
<td>–</td>
<td>✓</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?)</td>
<td>✓ (?</td>
</tr>
</tbody>
</table>

The different tasks place different demands and constraints upon the performer, as indicated by ticks and crosses, and are thus likely to exploit different
courses of information. The distinction between tasks is not hard and fast but somewhat ‘fuzzy’, hence the question marks (?) which are used to indicate
that there are likely to be conditions under which the opposite to the marked symbol might be the case. (MT = movement time; First-order TTC = time to collision estimate that ignores acceleration.)
task. A new framework for understanding TTC perception, very different from the Gibsonian theory, is outlined here. This framework is based, firstly, upon results that demonstrate that many different cues are used to estimate TTC and that their use is task dependent, and secondly, on the idea that biological perceptual systems are continuously adapting opportunities for learning machines, constrained by task requirements, stimulus conditions and neural information-processing limitations. This framework is capable of integrating all the theoretical and empirical work on TTC estimation that has been published. It emphasizes the critical importance of task constraints in determining the perceptual cues used in the performance of visually timed behaviours and raises many challenges and questions for future research into TTC perception.

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My thanks to James Cutting, Gay Wallis and two anonymous referees for helpful comment on previous versions of the manuscript. Preparation of this manuscript was supported by the Australian Research Council.

References
Speechreading: illusion or window into pattern recognition

Dominic W. Massaro

In the Fuzzy Logical Model of Perception (FLMP) perceivers are conceptualized as forming perceptual judgments by evaluating and integrating multiple ambiguous sources of information, in an optimal manner based on relative goodness of match. This model has been tested favorably against a variety of competing theories and models. Recent extensions of the FLMP are described in this article along with empirical applications and verification, and progress in the study of speech perception by ear and eye is reviewed within this general theoretical framework. The model illuminates the differences that are observed across different languages in terms of information as opposed to information-processing. Pattern recognition of bimodal speech is representative of pattern recognition in a variety of other domains, such as emotion perception, and there are several domain-dependent reasons why multimodal presentation of audible and visible speech is particularly conducive to accurate pattern recognition. We believe that the positive outcome of this research provides a framework for the development of computer-animated agents, which can serve as language tutors and as conversational characters in other domains, easing the interaction of humans and machines.